Impact of Broadband Penetration on U.S. Farm Productivity

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Abstract

This paper uses data on broadband connections and the production and sales of agricultural products to empirically estimate the impact of improved connectivity on U.S. farming outcomes. The Federal Communications Commission has detailed data on broadband subscriptions from its semi-annual Form 477 collection. The USDA's National Agricultural Statistics Service (NASS) releases a complete census of agriculture every five years to measure agricultural activity. By pairing periodic releases of the Form 477 data collection with information on farm production expenses and crop yields from corresponding releases of the Census of Agriculture, the analysis directly evaluates the benefit of rural broadband development on the U.S. farming industry. Overall, I find evidence of crop yield improvements from increased Internet penetration rates at thresholds of 25 Megabits-per-second download and 3 Megabits-per-second upload speeds. Among the findings, a 1% increase in the number of 25+/3+ connections per 1,000 households is associated with a 3.6% increase in corn yields, as measured in bushels per acre. I also find some evidence of cost savings at thresholds of 10 Megabits-per-second download and 0.768 Megabits-per-second upload speeds. A 1% increase in the number of 10+/0.768+ connections per 1,000 households is associated with a 2.4% decrease in operating expenses per farm operation. The paper also provides an introductory look at changes in the composition and speed thresholds of connectivity available for selected field crops over time.

These working papers are intended to stimulate discussion and critical comment within the FCC, as well as outside the agency, on issues that may affect communications policy. The analyses and conclusions set forth are those of the authors and do not necessarily reflect the view of the FCC, other Commission staff members, or any Commissioner. Given the preliminary character of some titles, it is advisable to check with the authors before quoting or referencing these working papers in other publications. All titles are available on the FCC website at https://www.fcc.gov/reports-research/working-papers/.

Impact of Broadband Penetration on U.S. Farm Productivity

Katherine LoPiccalo[1]

1. Introduction

The U.S. agricultural sector has undergone a significant transformation in recent years as it has adapted information and telecommunications technologies to farm management practices. High-speed Internet connectivity is considered an essential component of modern agriculture, as farmers and industry stakeholders report increasing reliance on broadband to remain competitive and operate efficiently.[2] Broadband facilitates not only timely access to and the transmission of data, but is also necessary for data applications that automate field processes or otherwise improve business process outcomes for farmers.[3] While the qualitative link between connectivity and farming outcomes is likely undisputed, it remains to be credibly established how strong the link is quantitatively. What is the impact of improved connectivity on farming yields? Does high-speed broadband generate cost savings for farmers, and if so, are they significant? Such quantitative answers are important as policymakers and other stakeholders weigh the costs and benefits of subsidies and incentives for improved connectivity.

In this paper, I use data on broadband connections from the Federal Communications Commission and farming data from the U.S. Department of Agriculture's Census of Agriculture to uncover the relationship between improved connectivity and various U.S. farming outcomes. Improved connectivity is defined in this study as the increase over time in the number of Internet connections per 1,000 households at specific speed thresholds in farming counties. The aim of the analysis is to study the nexus between rural infrastructure development, digital technologies and agricultural practices, expanding the discussion and understanding of these interrelationships. Previous studies and industry estimates find suggestive evidence that Internet connectivity leads to improved outcomes for connected farms. To my knowledge there exists no rigorous, quantitative evaluation of this question using the highly disaggregated data on broadband connections collected by the Commission. This paper also provides a preliminary look at changes over time in the composition of connectivity in regions where a selected set of five field crops are produced (e.g., corn, cotton, hay, soybeans and wheat). Therefore, this study is a useful addition to the body of research supporting policy recommendations focused on

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[1] The initial research was performed while I was an economist at the Federal Communications Commission. I am currently an economist at the Consumer Financial Protection Bureau. The views expressed are my own and do not reflect those of the Consumer Financial Protection Bureau, the FCC or the U.S. government. I would like to thank Jonathan Levy, Jeffrey Prince, Glenn Woroch, Aleks Yankelevich, anonymous reviewers and seminar participants at the FCC for their helpful comments and suggestions.

[2] "For farmers, broadband is a necessity, not a luxury," Zippy Duvall, president of the American Farm Bureau Federation, Opinion Contributor, The Hill. Nov. 1, 2018, https://thehill.com/blogs/congress-blog/technology/414370-for-farmers-broadband-is-a-necessity-not-a-luxury, last accessed May 19, 2020; *See, e.g.*, Jeffcoat et al. (2012).

[3] This may include changes from the hardcopy distribution of information necessary to operate efficiently to online delivery or the digitization of back-office functions and recordkeeping. *See, e.g.*, Matherly (2016); "A Case for Rural Broadband: Insights on Rural Broadband Infrastructure and Next Generation Precision Agriculture," U.S. Department of Agriculture, American Broadband Initiative, April 2019.

promoting the rapid, expanded diffusion of Internet access on unserved and underserved agricultural land.

1.1 Addressing the Digital Divide

The Commission has previously addressed the importance of high-speed Internet connectivity and has stated that further efforts are required to expand broadband to underserved and unserved agricultural land. Additionally, the Commission is charged by Congress to "encourage the deployment on a reasonable and timely basis of advanced telecommunications capability to all Americans," by removing barriers to infrastructure investment and by promoting competition in the telecommunications market.[4] Broadband has been clearly show to be a key contributor to economic development, job creation, education and civic engagement.[5] In its 2016 Broadband Progress Report, the FCC stated that "Americans continue to turn to advanced telecommunications capability for every facet of daily life."[6] In the 2018 Broadband Progress report, the Commission reemphasized the need to "take concrete steps toward closing the digital divide,"[7] or the gap between "those who can use cutting-edge communications services and those who do not."[8] While progress has been made to reduce both the number of Americans and regions without access to high-speed broadband, many areas – particularly rural areas – remain either underserved or unserved altogether. While 93.5% of Americans overall had access to high-speed fixed service in 2017, only 26% of rural Americans had access to high-speed fixed service in 2017, according to the 2019 Broadband Deployment Report.[9] Closing the digital divide has been a top priority of the Commission for the last several years, and the 2020 Broadband Deployment Report states that more Americans than ever have access to high-speed broadband.[10] The 2020 report states that the number of people in the U.S. without access to fixed terrestrial broadband service at speeds of 25 Megabits-per-second download and 3-Megabits-per-

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[4] 47 U.S.C. SS 1302(a). Congress also entrusted this responsibility to state commissions; In the Matter of Communications Marketplace Report, The Stata of Mobile Wireless Competition, Status of Competition in the Market for the Delivery of Video Programming, Status of Competition in the Marketplace for Delivery of Audio Programming, Satellite Communications Services for the Communications Marketplace Report, adopted Dec. 12, 2018, Released Dec. 26, 2018.

[5] "In the Matter of Rural Digital Opportunity Fund Connect American Fund", Notice of Proposed Rulemaking, WC Docket No. 19-126 and WC Docket No. 10-90, released Aug. 2, 2019, page 1.

[6] "In the Matter of Inquiry Concerning Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion, and Possible Steps to Accelerate Such Deployment Pursuant to Section 706 of the Telecommunications Act of 1996, as Amended by the Broadband Data Improvement Act," 2016 Broadband Progress Report, released January 29, 2016, Federal Communications Commission, GN-Docket No. 15-191, pg. 3.

[7] "In the Matter of Inquiry Concerning Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion," 2018 Broadband Progress Report, released February 2, 2018, Federal Communications Commission, GN-Docket No. 17-199, page 5.

[8] Ajit Pai, FCC Chairman, First remarks as Chairman of the FCC to agency staff. Accessed through "Setting the Record Straight on the Digital Divide," Feb. 7, 2017 (https://www.fcc.gov/news-events/blog/2017/02/07/setting-record-straight-digital-divide, last accessed Dec. 12, 2020).

[9] High-speed fixed service refers to broadband at speeds of 25 Megabits-per-second download and 3 Megabits-per-second upload speeds ("In the Matter of Inquiry Concerning Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion," 2019 Broadband Deployment Report, released May 29, 2019, Federal Communications Commission, GN-Docket No. 18-238, pg. 3).

[10] "In the Matter of Inquiry Concerning Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion," 2020 Broadband Deployment Report, released April 24, 2020, Federal Communications Commission, GN-Docket No. 19-285, page 2.

second upload declined by more than 14% in 2018 and by more than 30% between 2016 and 2018.[11] Despite recent improvements, however, gaps remain for Americans in rural and Tribal areas in terms of high-speed broadband and access to advanced telecommunications services.[12]

Several programs are administered by the Commission and targeted to increasing the availability of fixed and mobile broadband services in underserved and unserved areas. The Commission's Universal Service Fund (USF) provides funding to programs and policies that ensure all Americans have access to communications services. While originally focused on telephone (voice) service, current universal service policies at the Commission recognize the importance of high-speed broadband in communications technology. Within the Universal Service Fund, the Commission administers four programs to increase the availability of voice, fixed and mobile broadband services in unserved and rural areas: Connect America Fund (CAF) for rural areas; Lifeline for low-income consumers; E-rate for schools and libraries, and; the Rural Health Care initiative.[13]

The Connect America Fund (also known as the universal service high-cost program) supports that consumers in rural and high-cost areas have access to modern telecommunications networks providing voice and broadband service at rates that are reasonably comparable to those in urban areas. The CAF rolled out in two phases, with the first phase transitioning legacy support to a new auction mechanism. In 2018, the Commission announced that 103 winning bidders would receive $1.488 billion in subsidies over 10 years to serve 713,176 rural homes and small businesses. On Aug. 1, 2019, the FCC adopted a Notice of Proposed Rulemaking (NPRM) to establish a Rural Digital Opportunity Fund to distribute $20.4 billion in USF subsidies targeting at least 4 million rural homes and small business in unserved areas over 10 years.[14] As of October 2019, the Commission has approved six waves of funding from its CAF Phase II auction totaling approximately $1.2 billion.[15] The Commission has also taken steps to make universal service support available to mobile providers. In April 2020, the Commission issued a Notice of Proposed Rulemaking and Order that would propose to establish the 5G Fund to make up to $9 billion in USF subsidies available over 10 years to carriers to deploy advanced mobile wireless services throughout rural America.[16] Additionally, the 5G Fund would set aside at least $1 billion in support for deployments that address precision agriculture needs.[17] In 2019, the

[11] FCC 2020 Broadband Deployment Report, April 24, 2020, page 2.
[12] FCC 2020 Broadband Deployment Report, April 24, 2020, page 5.
[13] FCC-18-181A, Connect America Fund et al, Report and Order and Further Notice of Proposed Rulemaking, 26 FCC Rcd 17663, 17668-69, paras. 1-5 (2011) (USF/ICC Transformations Order), aff'd sub nom, In re: FCC 11-161, 753 F.3d 1015 (10th Cir. 2014).
[14] *See, e.g.,* RDOF NPRM, Aug. 2, 2019.
[15] The CAF Phase II auction funds, $116.6 million for 37,148 homes in 12 states over 10 years. On June 10, the FCC announced the second wave of funding for rural broadband from its CAF Phase II auction for Universal Service Fund broadband subsidies; on Aug. 12, 2019, it announced $121 million in funding over 10 years to expand broadband to 36,579 unserved rural homes and businesses in 16 states as part of the fourth; On Sept. 12, 2019, the FCC authorized $112.2 million in funding over 10 years to expand broadband to nearly 48,000 unserved rural homes and businesses in nine states, representing the fifth wave of support from the 2018 CAF Phase II auction.
[16] Notice of Proposed Rulemaking and Order (FCC 20-52), GN Docket No. 20-32. FCC Proposes the 5G Fund for Rural America (https://docs.fcc.gov/public/attachments/DOC-363946A1.pdf).
[17] Precision agriculture is generally categorized as farm management technologies that take advantage of timely, detailed and site-specific data (Schimmelpfennig and Ebel, 2016). The 5G Fund replaced the planned Mobility Fund Phase II (MF-II). The MF-II program was designed to distribute up to $4.53 billion in support available over 10

FCC announced the formation of a new task force in support of provisioning connectivity on unserved agricultural land that can be used by U.S. agricultural producers.[18] The task force provides advice and recommendations for the Commission on how to assess and advance deployment of broadband and to promote agricultural practices that rely on real-time data and metrics.

1.2 Purpose of the Present Study

This paper uses data on broadband connections and the production and sales of agricultural products to empirically estimate the impact of improved Internet connectivity on U.S. farming outcomes. Improvement in connectivity is defined as the increase in the penetration of broadband connections at either a minimum threshold of 25 Mbps download and 3 Mbps upload speeds, or a minimum threshold of 10 Mbps download and 0.768 Mbps upload speeds. The analysis seeks to determine whether farms in counties with higher broadband penetration rates fare better over time in terms of higher crop yields or lower production expenses than those in counties with lower levels of Internet penetration. Policy makers in the agricultural and telecommunications sectors have long supported the expansion of rural broadband.[19] This study adds to that discussion by evaluating how increased broadband penetration rates affect business outcomes for U.S. farms.

The Commission has detailed internal data on broadband connections from its semi-annual Form 477 collection. USDA's National Agricultural Statistics Service (NASS) releases a Census of Agriculture every five years to measure agricultural activity. By pairing periodic releases of the Form 477 data collection to information on farm expenses and crop yields from corresponding releases of the Census of Agriculture, this study directly evaluates the benefit of rural infrastructure development on the U.S. farming industry from 2007 to 2017.

The present study innovates over the existing literature in several important ways. First, the paper is the most comprehensive study to make extensive use of the Commission's internal Form 477 data on broadband connections by speed threshold and technology of transmission (e.g., cable or Asymmetric DSL) over time to examine the research question. Second, I construct a panel to estimate the extent to which improvements in Internet penetration at two speed thresholds result in better business outcomes for farm operations. This rich dataset allows a more direct estimate of the causal relationship between improved connectivity and farming outcomes as a function of other county-level characteristics such as median household income, the

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years to increase access to 4G Long Term Evolution (LTE) service in primarily rural areas (https://www.fcc.gov/mobility-fund-phase-ii-mf-ii, last accessed Dec. 12, 2020).

[18] Congress directed the FCC, in consultation with the Secretary of the Department of Agriculture, to establish the task force in the Agricultural Improvement Act of 2018 (2018 Farm Bill); "FCC Announces the Establishment of the Task Force for Reviewing Connectivity and Technology Needs of Precision Agriculture in the United States and Seeks Nominations for Membership," Public Notice, DA 19-568, Federal Communications Commission, released June 17, 2019.

[19] *See, e.g.,* "A Case for Rural Broadband," USDA, April 2019; 2020 Broadband Deployment Report, April 24, 2020, Federal Communications Commission.

unemployment rate, population density and area education levels, among other demographic characteristics.[20]

Overall, I find robust evidence that improved connectivity using a threshold of at least 25 Mbps download and 3 Mbps upload speeds (25+/3+) result in higher crop yields. Corn, cotton, hay, soybeans and wheat yields are all positively and significantly correlated with increased 25+/3+ broadband penetration rates. Among my findings, a 1% increase in the number of 25+/3+ connections per 1,000 households in a county is associated with an approximately 3.6% increase in corn yields, and a 3.8% increase in soybean yields. While the results for all five crops are not as strong at the slower 10+/0.768+ speed threshold, I do find that a 1% increase in 10+/0.768+ broadband penetration rates is associated with a 5.5% and 3.6% increase in corn and soybean yields, respectively. By contrast, this study finds lower production expenses per farm operation at the 10+/0.768+ threshold. I find, for example, that a 1% percent increase in the number of 10+/0.768+ connections per 1,000 households is associated with an approximately 6.5% decline in fertilizer expenses per operation and a 3.4% decrease in seed and plants expenses per operation. These results indicate farm operations in counties with increased 10+/0.768+ broadband penetration rates from 2007 to 2017 realized lower operating expenses on average than counties without increased penetration during the same time frame. The evidence remains mixed for expense improvements from increased broadband penetration rates at the 25+/3+ threshold. Further discussion of these results is given in Section 5.

The findings contribute to a body of literature that builds directly on work that examines the impact of Internet on a range of outcomes, including health (Whitacre and Brooks, 2014), jobs and economic productivity (Atif et. al., 2012). The paper is most closely associated with studies measuring the effect of broadband service or e-Commerce expansion in rural communities (Atif et. al., 2012) and on farms (Kuttner, 2016; Kim and Orazem, 2016). However, empirical analyses of the benefits of Internet connectivity on farms remain mixed in other contexts (Achenreiner and Cylhoff, 2005; Guo et. al., 2018; Stenberg et al., 2009). Studies have found that improved connectivity may contribute directly to sales growth and profitability by lowering input or other supply costs. Access to the Internet decouples purchasing patterns from spatial constraints by providing farmers the ability to comparison shop for farm inputs, machinery, and even credit among local, near local or national suppliers (Just and Just, 2001; Achenreiner and Dylhoff, 2005; Stenberg et. al., 2009; Jeffcoat et. al., 2012). Evidence suggests that U.S. farmers use e-Commerce to obtain lower prices on seeds, herbicides and other crop supplies.[21]

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[20] While the data comprehensively archive broadband technologies in U.S. census tracts over time, collection and reporting methodologies limit some of the analyses I'm able to perform. For instance, the paper relies on fixed terrestrial broadband services (including fixed terrestrial wireless) and satellite connections but excludes terrestrial mobile wireless technology. The Commission's Form 477 collected data on terrestrial mobile wireless at the state level, while data for other technologies of transmission were collected at the census tract level. See Section 3 on data for an extensive definition and description of broadband terminology.

[21] "E-Commerce for Farmers: Shopping Online for $26,000 of Herbicides", Wall Street Journal, Jesse New and Jacob Bunge, Feb. 16, 2017; An earlier article finds that connectivity can contribute savings of up to 30 percent by eliminating suppliers and distributors for seeds, fertilizers and crop protection chemicals ("Old Mac Donald Has a Website: Online exchanges for farmers are cutting costs for seed, feed, and chemicals while boosting prices for products," Darnell Little, Businessweek (now Bloomberg Businessweek), May 15, 2000

Further studies indicate that broadband adoption is not homogenous across farms. Farms further upstream (e.g. feed suppliers) are more likely to adopt the Internet and engage in e-Commerce (Henderson et. al., 2004). Likewise, larger firms are more likely to adopt broadband, engage in e-Commerce, and create an online presence through digital marketing strategies (Smith et. al., 2004; Burke, 2009). Large agribusiness firms with an international scope are more likely to adopt Internet use than others whose scope remains more local (McFarlane et. al., 2003; Ehmke et. al., 2001). Other factors that contribute to broadband adoption include farmer age and educational achievement, family size, and previous exposure to computers and the Internet (Briggeman and Whitacre, 2010; Mishra et. al., 2009; Mishra and Williams, 2006; Gloy and Akridge, 2000; Smith et. al., 2004). This paper is also associated with literature estimating the impact of the USDA's Broadband Loan Program on economic outcomes for farmers (Dinterman and Renkow, 2017; Kandilov and Renkow, 2010; Kandilov et.al., 2011).[22] Broadly, the paper is related to literature examining the importance of broadband connectivity on "big data" applications as well as precision agriculture.

Some studies have identified a difference in the effect of broadband adoption vs. availability on outcomes of interest (Whitacre, Gallardo and Strover, 2014; Whitacre, Mark and Griffin, 2014). Historically, the Commission has measured broadband both in terms of *adoption rates* as well as *deployment rates*. Broadband availability is generally characterized by the deployment rate, which is the ratio of the population with access to fixed broadband service at or above a speed benchmark to the total population.[23] While historical data on broadband deployment and availability back to 2010 is publicly available, the Commission has also released publicly limited data on household broadband adoption rates and the number of providers at the county level since 2008.[24] The Commission has measured the adoption rate of services at or above a speed benchmark using both its Form 477 subscription and deployment data.[25] The adoption rate is the ratio of the number of residential Form 477 broadband subscriptions to the total number of households where the same minimum broadband speed of service has been deployed.[26]

(https://www.bloomberg.com/news/articles/2000-05-14/old-mac-donald-has-a-web-site, last accessed Dec. 12, 2020).

[22] To expand rural broadband availability, the USDA created a Broadband Loan Program to incentivize Internet service providers to increases service in rural areas (Dinterman and Renkow, 2017).

[23] The Commission has also calculated deployment rates using the number of housing units and the number of households.

[24] From 2010 to 2014, the National Telecommunications and Information Administration (NTIA) State Broadband Initiative (SBI) released to the public semi-annual data on fixed Internet availability by provider, technology type, and speed threshold at a census block level. The Commission took over this data collection in 2014. The publicly released data on adoption rates are split into five categories based on the proportion of household broadband adoption rates: proportion of households at less 20 percent adoption; from 20 percent to 39.9 percent adoption; 40 percent to 59.9 percent adoption; 60 percent to 79.9 percent adoption, and; 80 percent adoption and above.

[25] In June 2013, the Commission approved changes to the Form 477 collection that affected the data beginning in June 2014. Before 2014, the National Telecommunications and Information Administration (NTIA) oversaw the collection of data on broadband deployment in coordination with the States. Beginning in 2014, the FCC assumed responsibility for the collection of broadband deployment. The first filings at the FCC were due on Oct. 1, 2014, representing data as of June 30, 2014, while NTIA's final collection was also for data as of June 30, 2014. The FCC has collected census-tract level data as of Dec. 31, 2008. Post-2014, deployment and subscription data collection efforts were consolidated into the Form 477 data collections.

[26] FCC 2020 Broadband Deployment Report, April 24, 2020, GN-Docket No. 19-285, page 30.

The variable of interest in this paper is the broadband penetration rate, which is the ratio of the number of connections at given speed threshold in a county over the total number of households in a county.[27] While prior empirical studies have focused on the role of broadband access in facilitating job growth, firm creation or health outcomes, to my knowledge there are no empirical studies that directly measure the impact of rural broadband penetration on U.S. crop yields and farm expense measures. Further, no studies directly analyze farming outcomes with respect to broadband penetration at the county level using internal Commission data on the number broadband connections.

The rest of the paper proceeds as follows. Section 2 describes the link between Internet connectivity and farming outcomes. Section 3 describes the primary datasets and presents summary statistics. Section 4 describes the empirical strategy. I present results in Section 5. Section 6 provides a discussion of potential policy implications and concludes.

2. The Link Between Internet Connectivity and Farm Outcomes

It is useful to frame the analysis by identifying the various mechanisms through which Internet connectivity may influence farm outcomes. As stated in Section 1, broadband may impact farm profitability by directly lowering input or other supply costs. While online price discovery enables farmers to directly source materials at a lower cost, an indirect effect may be an improved bargaining position from the elimination of information asymmetries.[28] Access to online databases of nationwide prices provide farmers the ability to negotiate with their traditional suppliers for better prices, as farmers are no longer locked into offered rates from the local farm store or co-operative.[29] A corresponding argument could be made that connectivity enables farmers to obtain the highest prices for their crops or livestock via the same mechanisms. U.S. farmers may also depend on the Internet to access up-to-date information on weather and commodity markets, to automate record-keeping and reporting tasks, and to engage in online banking[30].

A more salient mechanism derives from the use of Internet connectivity to extract real-time, accurate data on crop yields, soil moisture levels, plant health, and equipment conditions.[31] Farm management technologies that take advantage of timely, detailed and site-specific data are classified broadly as "precision agriculture."[32] More specifically, precision agriculture (PA) is a "management strategy that gathers, processes and analyzes temporal, spatial and individual data and combines it with other information to support management decisions according to estimated

[27] Although the results are not included in this paper, the main empirical regressions were also run using housing units and total population as the denominator in the penetration rate, with little change in the ultimate findings.
[28] McFarlane et. al., 2003; Ibid, footnote 21, page 8.
[29] McFarlane et. al., 2003. Ibid, footnote 21, page 8.
[30] *See, e.g.,* Briggeman and Whitacre (2010); United Soybean Board, White Paper (2019).
[31] Ibid, footnote 30.
[32] *See e.g.,* Schimmelpfennig and Ebel (2016).

variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production."[33]

PA technologies are varied but are generally grouped into three categories that may be implemented either sequentially or in tandem: monitoring and sensing applications; variable rate technology; and farm operation applications (i.e. data management systems).[34] Farmers may choose to integrate one or several PA technologies into the farm management process, but all processes depend significantly on high-quality Internet connectivity. Monitoring and sensing applications most often include GPS-based mapping of yield and soil data, unmanned aerial vehicles or drones, and remote soil sensors that generate real-time data on soil nutrient levels.[35] Computer mapping using GPS and variable rate technologies enables targeted input application or management of low-yielding or less-productive subareas within larger farm fields. Satellite-guided auto-steer systems for combines and tractors improve accuracy in tilling, planting, and spraying, particularly when paired with telematics, or the real-time data collection for machine and harvesting efficiency management. Information generated by PA technologies can then be transmitted via short-range wireless or WiFi technologies (which are more efficient than a manual transfer of collected data) to cloud-based farm data management systems for further analysis. According to industry estimates, technological innovation made possible by precision agriculture and the deployment of broadband, has "lowered farm expenses on seed, fertilizer and pesticides by an average of 15 percent, and raised crop yields by an average of 13 percent."[36]

Precision agriculture applications depend on both within-farm infrastructure and a robust connection to the Internet. Farms can implement these technologies in similar ways as home broadband connectivity devices are used in the residential context. Farms have the option of purchasing additional fixed or wired lines through their Internet service provider (ISP) to connect barns or other outbuildings. Farms may also extend a single home or base wired or satellite connection to fields, tractors, barns or outbuildings via antennas, extenders or repeaters.[37] More formally, some companies offer mesh systems that use standard WiFi signals and Ethernet connectivity that connect to a router and transmit that connectivity to hubs and receivers across fields, tractors, barns and other outbuildings.[38]

Reliable and affordable high-speed broadband connectivity has the capacity to further transform the U.S. farming industry.[39] Ge, Thomasson and Sui (2012) illustrate this potential in related work describing field tests of a wireless-and-GPS system for mapping cotton fiber quality. According to the authors, cotton prices are based on fiber quality, therefore identifying

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[33] "ISPA Forms Official Definition of 'Precision Agriculture'", PrecisionAg.com, International Society for Precision Agriculture (https://www.precisionag.com/market-watch/ispa-forms-official-definition-of-precision-agriculture/, last accessed Oct. 24, 2019).
[34] *See e.g.,* Schimmelpfennig and Ebel (2016).
[35] *See, e.g.,* Bramley (2009); Schimmelpfennig and Ebel (2016).
[36] *See, e.g.,* CoBank Report, March 2016.
[37] "Best WiFi for Rural Areas: The Definitive Guide", Simple WIFI (https://www.simplewifi.com/blogs/news/best-wifi-for-rural-areas-extenders-repeaters, last accessed Dec. 12, 2020).
[38] Ayrstone Productivity (https://ayrstone.com/www/how-it-works/longer-range-networks/, last accessed Nov. 22, 2020); "Boost wireless signals around the farm," Jessica Michael, Farm Progress (https://www.farmprogress.com/blogs-boost-wireless-signals-around-farm-10265, last accessed Dec. 10, 2020).
[39] https://www.cnet.com/news/in-rural-farm-country-forget-broadband-you-might-not-have-internet-at-all/

spatial variability in quality across fields could benefit farmers by focusing crop inputs to optimize quality and yield. Manually testing and mapping cotton fiber quality is both time and resource intensive, especially during the cotton harvest when workers' attentions are concentrated on ensuring the harvest is completed quickly with minimal degradation in quality. Upgrading harvesting and dumping equipment with sensors that automatically record position data for each harvested basket of cotton, farmers can pair that location data to the quality classification of cotton modules done by USDA Agricultural Marketing Service classing offices.[40] After harvesting and classification, data from the wireless-and-GPS-enabled system can be downloaded for GIS analysis, fiber-quality mapping and other post-processing procedures. Paired with yield maps and other data, the system can be used to increase not only future crop quality but yield and farm profitability. The authors also find some potential to reduce energy use, labor time and stress or fatigue on the farmer.

3. Data

Several data sources are combined to determine the relationship between improved broadband connectivity and farming outcomes. The dependent variables are derived from three successive waves of the USDA's Census of Agriculture (Ag. Census). The Ag. Census is a complete record of U.S. farms and ranches and the people who operate them.[41] All plots of land, whether rural or urban, are included in the census if agricultural products valued at $1,000 or more were produced and sold – or normally would have been sold – during the census year.[42] The census is taken once every five years for years ending in 2 and 7 and "provides the only source of uniform, comprehensive, and impartial agriculture data for every county in the nation."[43]

The primary analysis focuses on both farm expenses – chemical, seed and plants, fertilizer, fuel and operating expenses per operation – as well as production (yield) measures for five row crop commodities – corn, cotton, hay, soybeans and wheat – from the 2007, 2012, and 2017 censuses. The row crop commodities are chosen for two reasons: 1) related literature indicates that row crops such as corn, soybeans, wheat and cotton are more likely to benefit from improved connectivity since they have been targeted for the application of precision agriculture technologies like yield monitors; and 2) the Ag. Census data indicate they are among the top commodities in the U.S. in terms of production.[44]

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[40] Cotton classing office locations: https://www.ams.usda.gov/about-ams/programs-offices/cotton-tobacco/classing-offices, last accessed Dec. 7, 2020.

[41] Collection is done by the USDA's National Agricultural Statistics Service (NASS). According the USDA's report form guide for the 2017 Census of Agriculture, "a census of agriculture is taken to measure agriculture activity and productivity for each county and state of the United States. A national census of agriculture was first taken in 1840 and was conducted every 10 years thereafter until 1920. Since 1982, the Census of Agriculture has been conducted on a 5-year cycle for years ending in 2 and 7."

[42] Census of Agriculture, USDA, Frequently Asked Questions (https://www.nass.usda.gov/AgCensus/FAQ/2017/index.php, last accessed Dec. 11, 2020).

[43] https://www.nass.usda.gov/AgCensus/, last accessed Dec. 11, 2020.

[44] *See, e.g.*, Whitacre, Mark, and Griffin (2014); According to the U.S. Department of Agriculture, corn, soybeans and wheat are the top U.S. field crops in planted acreage, production, and gross farm receipts (https://www.ers.usda.gov/topics/crops/wheat/wheat-sector-at-a-glance/, last accessed Nov. 24, 2020).

Note that the yield data are crop specific while the expense measures are farm specific. The Ag. Census data do not distinguish expenses by crop type, it is an aggregate measure across all operation types including aquaculture, animal farming, and nurseries. It is useful to study yields because they are directly related to productivity. Since precision agriculture may impact crops differentially, crop-specific data are well suited to the purpose. On the other hand, expenses are closely tied to profitability and are therefore also important to study. Since precision agriculture likely affects crop production differentially, it would be ideal to have expense data that exists at the crop level. As noted above in the case study of cotton, some precision agriculture techniques are applied post-harvest and so the impact would not show up in yields. While the impact would show up in expenses, those data are not available per crop.

Limited descriptive analysis focuses on select machinery that may be related to precision agriculture, including the number of self-propelled combines, cotton pickers and strippers, and forage harvesters, in use and purchased by farm operators, particularly those purchased within five years. They are not included formally in the modeling because there is no method of linking this machinery use to the production processes of farms specifically engaged in corn, cotton, hay, soybean or wheat production. Additional control variables relating to county agriculture production characteristics, specifically average farm size (both overall and by crop type) or the average number of workers per operation, are drawn from the Agricultural Census and included in the formal modeling. The Agricultural Census data exist at the county level.

The primary independent variables of interest are derived from internal FCC subscription data and exists in its native format at the census tract level.[45] The Commission collects broadband subscribership data through its semi-annual Form 477 data collection. The Form 477 collection gathers standardized information about the number of Internet access connections by provider, downstream and upstream speeds, technology of transmission (e.g., cable modem or Asymmetric DSL), and end-user type (e.g., residential vs. business), over time and across census tracts through semi-annual data releases. Connections are also classified according to nine technology types. Figure 1 enumerates these technology categories. Fixed broadband access connections are defined in the data as "wired 'lines' or fixed terrestrial wireless 'channels' " in service with transfer rates exceeding 200 kilobits per second (kbps) in at least one direction.[46] The Form 477 data collection also includes census tract level connections from satellite transmission. The analysis relies on fixed terrestrial Internet services, including terrestrial fixed wireless service, and satellite Internet connections.[47] Evidence suggests that satellite Internet

[45] Census tracts are small, relatively permanent statistical subdivisions of a county or equivalent entity, according to the U.S. Census (https://www.census.gov/programs-surveys/geography/about/glossary.html, last accessed Dec. 12, 2020). Census tracts generally have a population size between 1,200 and 8,000 people, with an optimum size of 4,000 people. (See 2010 Census Summary File 1 Urban/Rural Update Technical Documentation prepared by the U.S. Census Bureau, 2012, at A-12, http://www.census.gov/prod/cen2010/doc/sf1.pdf. A census tract usually covers a contiguous area; however, the spatial size of census tracts varies widely depending on the density of the settlement. See United States Census Bureau, Geographic Terms and Concepts – Census Tract (https://www.census.gov/geo/reference/gtc/gtc_ct.html, last accessed March 4, 2020).

[46] Fixed Broadband Subscription, FCC Form 477 definitions sheet.

[47] While some data on terrestrial mobile wireless connections are available beginning with the December 2008 data collection, providers were not required to report this information at the census tract level. Instead, providers of facilities-based mobile wireless service reported the "census tracts in the state that best represent the areas where service is available over the provider's own network, for each of the speed tiers in which the provider offers service"

may not be fully capable of supporting advanced precision agriculture technologies due to higher latency, capacity constraints, and higher costs for securing data flows.[48] However, this study remains agnostic with respect to technologies of transmission. To the extent a transmission technology is capable of providing a connection at a given speed threshold in the analysis, that connection is included.

Figure 1: Technology Types in Form 477 Collection

Technology Codes	
Type	**Description**
1	Asymmetric DSL
2	Symmetric DSL
3	Other Wireline
4	Cable Modem
5	Fiber-to-the-premises (FTTP)
6	Satellite
7	Terrestrial Fixed Wireless
8	Terrestrial Mobile Wireless
9	All Other

Internet access connections are classified according to eight download speed categories and nine upload speed categories (shown in Figure 2). Form 477 subscription data from December 2014 and later include the paired download and upload speeds (in Mbps) for each observation, while earlier vintages provide speed characteristics by paired download and upload tiers only.[49] Therefore, the analysis is restricted to the use of speed tiers in order to maintain consistency across all vintages of the 477 data.[50] Connections are aggregated from the census tract to the county level for a given speed threshold. The primary independent variable of interest is the number of connections at or exceeding 25 Mbps download and 3 Mbps upload speeds per 1,000 households in a county. An alternative measure uses the threshold of 10 Mbps download and 0.768 Mbps upload speeds per 1,000 households. I focus on 25+/3+ connections for two reasons: 1) 25+/3+ is the current FCC definition of "high-speed" broadband Internet[51], and 2) literature

("Internet Access Services: Status as of December 31, 2009," Federal Communications Commission, Industry Analysis and Technology Division, Wireless Competition Bureau, December 2010, page 81).

[48] "A Case for Rural Broadband," USDA, April 2019, page 7.

[49] Connections are classified by a paired download and upload speed, for instance: the number of residential connections using Asymmetric DSL with a download speed greater than or equal to 3 Mbps and less than 6 Mbps and an upload speed greater than or equal to 768 kbps and less than 1.5 Mbps.

[50] I convert enumerated upload and download speeds in their corresponding speed tiers using the classification scheme of earlier Form 477 collections.

[51] In 2015, the Commission concluded the broadband speeds of 4 Megabits per second download and 1 Megabit per second upload were no longer sufficient to be considered advanced telecommunications capability, and instead adopted the benchmark of download speeds of at least 25 Mbps and upload speeds of at least 3 Mbps. See "In the Matter of Inquiry Concerning Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion, and Possible Steps to Accelerate Such Deployment Pursuant to Section 706 of the Telecommunications Act of 1996, as Amended by the Broadband Data Improvement Act," 2015 Broadband Progress Report and Notice of Inquiry on Immediate Action to Accelerate Deployment, released February 4, 2015, Federal Communications Commission, GN-Docket No. 14-126.

suggests higher thresholds are required for some applications of precision agriculture, although not all applications.[52]

Figure 2: Speed Thresholds in Form 477 Collection

Upload/Download Rates	
Tier	**Description**
1	Less than or equal to 200 kbps (upload rates only)
2	Greater than 200 kbps and less than 768 kbps
3	Greater than or equal to 768 kbps and less than 1.5 Mbps
4	Greater than or equal to 1.5 Mbps and less than 3 Mbps
5	Greater than or equal to 3 Mbps and less than 6 Mbps
6	Greater than or equal to 6 Mbps and less than 10 Mbps
7	Greater than or equal to 10 Mbps and less than 25 Mbps
8	Greater than or equal to 25 Mbps and less than 100 Mbps
9	Greater than or equal to 100 Mbps

Estimation of the sample data and descriptive statistics include market and demographic characteristics from several sources. County-level demographic data from the U.S. Census Bureau include overall population, population by age cohorts, population by race, population share by educational attainment, median household income and median age.[53] Data on the unemployment rate from the BLS is included the analysis. The percent of farm proprietors' employment in each county from the Bureau of Economic Analysis is included in the descriptive characteristics. Data on the total number of establishments, number of establishments in the agriculture sector and in crop production, total employed in all establishments, and average annual pay in a county, from the Bureau of Labor Statistics' (BLS) Quarterly Census of Employment and Wages are included in the descriptive analysis. Counties can be designated metropolitan (i.e. larger labor market areas) or non-metropolitan using the USDA's Economic Research Service's rural classification scheme in the descriptive analysis. According to the ERS, nonmetro counties include some combination of open countryside, rural towns with fewer than

[52] One example of high bandwidth connected technologies is drone imagery of fields ("A Case for Rural Broadband," USDA, April 2019, pages 3 and 27).

[53] For 2007 household counts, I use 2005-2009 ACS 5-year Estimates for households, and for 2012 and 2017 household counts, I use FCC Staff Block Estimates (https://www.fcc.gov/staff-block-estimates). For 2007 housing units, I use the 2000-2010 intercensal data, and for 2012 and 2017, I use annual Census estimates of housing units and population from 2010-2018. For median household income, I use 2007-2017 Census data from the Small Area Income and Poverty Estimates (SAIPE) Program (https://census.gov/programs-surveys/saipe/data). For median age, population, population by gender, and population by age, I use Census data from the Annual Estimates of the Resident Population for Selected Age Groups by Sex for the United States, States, Counties and Puerto Rico Commonwealth and Municipios: April 1, 2010 to July 1, 2018, Release Date: June 2019. For other Census data, I use 2005-2009 ACS 5-year Estimates for 2007; the 2010-2014 ACS 5-Year Estimates for 2012; the 2014-2018 ACS 5-year Estimates is used for 2017 (NHGIS Data Citation: Steven Manson, Jonathan Schroeder, David Van Riper, and Steven Ruggles. IPUMS National Historical Geographic Information System: Version 14.0 [Database]. Minneapolis, MN: IPUMS. 2019. http://doi.org/10.18128/D050.V14.0.) Land area for each county derived from U.S. Census 2010 TigerLine Shapefiles and population counts.

2,500 people, and urban areas with populations ranging from 2,500 to 49,999 which are not part of the larger labor market areas (metropolitan areas).[54]

To assess the relationship between connectivity and farming outcomes, I first obtain the complete list of all U.S. counties or county equivalents from the Census Bureau. The analysis comprises the 48 contiguous states, and excludes Alaska, Hawaii, Puerto Rico and the U.S. territories of Guam, the U.S. Virgin Islands, N. Mariana Islands, and American Samoa. Each county is matched to its corresponding demographic attributes from the sources enumerated above. I construct a panel for approximately 3,070 counties across 3 time periods (2007/2008, 2012 and 2017), for a total of 9,210 observations in the pooled sample. Given the time series and cross-section components in the data, my analysis relies on changes in broadband penetration rates at different speed thresholds over time and across counties.

3.1 Data Limitations

The analysis has several limitations. Timing may be of key importance in estimating a causal effect of improved connectivity on farming outcomes. The mechanisms through which Internet connectivity affects farm outcomes would require that connectivity first be available for farms to incorporate into their production and management processes. Therefore, I cannot match the 2007, 2012, and 2017 Ag. Census collections, which report annual measures as of December 31 of each census year, with corresponding December vintages of the Form 477 data. Instead, I pair the 2012 and 2017 Ag. Census data collections with the June 2012 and June 2017 vintages of the Form 477 data, respectively. This pairing should support the requirement that connectivity be substantially available during the bulk of the planting, growing, and harvesting seasons.[55] As a robustness check, I also implement the main analysis pairing the December 2011 and December 2016 vintages of the Form 477 data with the 2012 and 2017 Ag. Census data collections.

However, December 2008 is the earliest vintage to which I can pair the 2007 Ag. Census data. The Commission began collecting census tract-level subscription data with the December 2008 release. The 2004 revisions of the Form 477 data collections did require all facilities-based providers to report broadband connections, but providers generally reported these counts at the state level and then provided a list of zip codes where broadband technologies were being used.[56] While recognizing that pairing December 2008 Form 477 data to 2007 Ag. Census data is less than ideal, this paper's primary analysis relies both on changes over time and across regions in both the dependent and independent variables of interest to infer causal impact. The estimated effect of improved connectivity from December 2008 to June 2012 on the change in farming outcomes from 2007 to 2012 should represent a lower bound, as the level change from December 2008 to June 2012 is lower than that from June 2007 to June 2012. It may be argued that bias

[54] https://www.ers.usda.gov/topics/rural-economy-population/rural-classifications/ (last accessed March 11, 2020).
[55] The season for field crops depends on the crop, location and soil temperature. Planting for corn, for instance, takes place from April to May (Sheperd and Harrington, 1998).
[56] *See, e.g., Modernizing the FCC Form 477 Data Program*, final rule, WC Docket No. 11-10 FCC 13-87, Effective September 12, 2013, 78 FR 49126, pages 49126-49149 (https://www.federalregister.gov/documents/2013/08/13/2013-19493/modernizing-the-fcc-form-477-data-program, last accessed Dec. 12, 2020).

may result if connectivity exhibits different patterns across census tracts from June 2007 to June 2012 as from December 2008 to June 2012. However, this is less of a concern for the primary empirical methodology, which relies on the change from one period to the next, and specifically for the first time period in the time series. As a robustness check, results are presented for both the full model – including the paired 2008 broadband and 2007 Ag. Census data – and a parsimonious model using only the paired 2012 and 2017 data from each source.[57]

Data limitations also preclude the use of terrestrial mobile wireless connections in the analysis. Terrestrial mobile wireless connection data was not collected at the census tract level in Form 477. To the extent that farm operations rely on cellular technology when wired or satellite broadband technology is unavailable or insufficient, this represents a disadvantage in the empirical methodology.

The paper's analysis is conducted at the county level, as the county is the smallest level of geographic disaggregation for which there is information on U.S. farming outcomes. Form 477 data are provided at the census tract level, while the Ag. Census data exist at the county level. The independent variable of interest is defined as the broadband penetration rate, or the total number of 25+/3+ or 10+/0.768+ connections per 1,000 households in a county. It is relatively straightforward to nest tracts within counties, but the differing levels of geographic aggregation between outcome and independent variables may affect precision of the results.

Earlier in the paper, I identified several mechanisms through which increased broadband penetration rates may influence farming outcomes. Broadband penetration may contribute to business process efficiency and sales growth through the reduction of input costs such as seeds and fertilizer, access to better information, or by lowering transportation or other transaction costs. Improved Internet access may also drive the adoption of farm management systems or precision agriculture technologies that facilitate increased production or lower costs. Data limitations preclude direct identification of these mechanisms at the farm level. The Ag. Census does not distinguish crop yields or farm expenses for farm operations that either have or do not have Internet, nor the speed thresholds of those connections. Therefore, while the analysis leverages changes in broadband penetration at specific speed thresholds over time and geography to uncover the potential impact on crop yields and farm expenses, the estimate of this link remains indirect. This limitation is consistent with related literature but does invite caution in evaluating the strength of any implied causality.

3.2 Descriptive Statistics

Tables 1 through 8 provide descriptive statistics for the data in the full sample. Table 1 reports on county-level means for general, expenses, land use, and selected Internet characteristics from the 2007, 2012 and 2017 waves of the Ag. Census. The Internet characteristics included in Table 1 are derived from the Ag. Census only, not from the Commission's Form 477 data collection. The first panel of Table 1 provides general information

[57] I also implement a limited analysis using only the first two periods (2007/2008 and 2012) to examine whether there are differing treatment effects over time.

on county-level farm operation characteristics for each time period, including the average number of operated acres, harvested acres of cropland, and the number of farm operations (e.g. farms) with operated acres. Cropland includes land from which field crops were harvested or hay was cut, and land used for vegetables, nursery and greenhouses, orchards, vineyards, citrus groves, Christmas trees, short rotation woody crops, fruits, nuts and berries.[58] The data indicate that while the average number of farm operations and farm operations with operated acres have declined slightly from 2007 to 2017, the number of operated and harvested acres of cropland have remained relatively stable. This seems to indicate that the average size of farms has increased over time, perhaps through larger farms acquiring smaller farms. Most of the selected expense characteristics (e.g. chemical, operating, and seed and plants expenses) indicate increasing county-level average expenses per operation over time, while others exhibit a peak in 2012 (e.g. fertilizer and fuel).[59] Again, farm expenses are not distinguished by crop type. Chemical expenses are an aggregate measure that includes insecticides, herbicides, fungicides, and other pesticides, and includes the costs of custom application.[60] It does not include the costs of commercial fertilizer. Operating expenses include all production expenses for all farm operation types, such as field crops, aquaculture and animal farming. Seed and plants expenses include the cost of all seeds, bulbs, plants, propagation materials, trees, seed treatments, and seed cleaning costs purchased in the Ag. Census year.[61] Most acres (either operated or not) are treated with fungicide, herbicide, insecticide and fertilizer. Relatively few farm operations employ self-propelled machinery, including combines, cotton pickers/strippers, or forage harvesters. Even fewer operations have self-propelled machinery that were manufactured in the last five years of the Ag. Census. More importantly, these numbers exhibit little change across all three waves of the Ag. Census. This seems to indicate relatively little implementation of at least one type of precision agriculture technology, but as noted previously, broadband can be integrated into many types of farm management processes. Additionally, this paper's estimation results suggest future adoption of some precision agriculture technologies may depend on high-speed broadband availability.

The Ag. Census collects limited information from farm operations about Internet use, including how farms connect to the Internet (e.g. cell phones, laptops, or tablets) and technology used (e.g. DSL or cable modem). In most cases, the data only exist for the 2012 and 2017 waves. Table 1 indicates that farm operations with Internet access have increased through each of the three waves of the Ag. Census, although the data does not include information about speed thresholds. For example, one survey question in the 2007 Ag. Census provides the number of farm operations with "high-speed Internet access," but the report form guide for the 2007 census does not specify which Internet service qualifies as "high speed" and would meet this threshold.[62] The data do indicate that a greater number of operations access Internet via mobile

[58] If two or more crops were harvested from the same land in the census year, the acres are counted for each crop and the total acres of all crops harvested could exceed the acres of cropland harvested (General Explanation and Census of Ag Report Form, Appendix B, 2017 Census of Agriculture, page 2).
[59] Total farm production expenses include the production expenses provided by the producers, landlords (excluding property taxes), and production
[60] General Explanation and Census of Ag Report Form, Appendix B, 2017 Census of Agriculture, page 22.
[61] It does not include items purchased for resale or the value of seed that is grown on the farm (General Explanation and Census of Ag Report Form, Appendix B, 2017 Census of Agriculture, page 24).
[62] The question in the 2007 survey is "At any time during 2007, did this operation have high speed Internet access?" (2007 Census of Agriculture, U.S. Department of Agriculture, National Agricultural Statistics Service, Report Form

wireless than wired connections such as FTTN or cable. Second, the number of operations using DSL or dialup technologies has significantly declined from 2012 to 2017.

Tables 2 through 6 report production and wired Internet characteristics for each of the five selected field crops in the counties where those crops are produced. The variables reported under the row title *General Characteristics* are drawn from the Ag. Census data and represent field crop averages for those counties in which that field crop was reported to have been harvested. For instance, Table 2 lists 2,319 counties in which at least some corn was harvested in 2007. In those 2,319 counties, there were on average approximately 150 farms with harvested acres of corn in 2007. Average county yield measures for each row crop are also given. Corn, soybeans, wheat and hay are produced across the U.S. in at least two-thirds of all counties in the full sample. Cotton is produced in relatively few counties across the U.S.

Wired and satellite broadband characteristics in Tables 2 through 6 are reported using the paired Form 477 data in all counties where a specific crop was harvested. Using the previous example of corn-producing regions, in the set of 2,319 counties where corn was harvested in 2007, 33.8% of all wired and satellite broadband connections were transmitted through cable modems in 2007 (December 2008), whereas 38.5% of all wired and satellite broadband connections were transmitted through cable modems in June 2017. Speed thresholds in corn, cotton, hay, soybean, and wheat regions are reported for matched download and upload rates and separately by download and upload speeds in Tables 2 through 6. Following past practice, speeds are in Megabits per second (Mbps). For two-way speed thresholds in corn-producing regions, Table 2 indicates the share of all connections that were at least 3 Mbps download speed and 0.768 Mbps upload speed increased from 19.8% in 2007 (December 2008) to 46.3% in 2012 and to 87.4% in 2017. Overall, the tables indicate that Internet penetration has significantly improved in each crop region from 2007 to 2017. This is true both in terms of the number of connections per 1,000 households overall, as well as the speeds of those connections. Connectivity at lower speed thresholds has declined in each crop region from 2007 and 2017, as the number higher speed connections has increased. In addition, the composition of wired broadband connections has transitioned from majority DSL (either Asymmetric or Symmetric) to cable modem and FTTN technology.[63]

Table 7 presents county-level means for other independent variables that could potentially impact observed changes in farming outcomes as well as descriptive characteristics at the county level. These variables were enumerated previously and include socio-economic controls such as the unemployment rate, population, age and median household income. Table 8 presents overall county-level means for broadband subscription characteristics for the 2008, 2012 and 2017 releases of the Form 477 data. Overall, the data show improvements in broadband

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Guide, Survey Form, Section 32. Practices, page 124) The only further clarification of the survey question is that "regardless of the provider, dial-up Internet access is not considered 'high speed' Internet access" (2007 Census of Agriculture, U.S. Department of Agriculture, National Agricultural Statistics Service, Report Form Guide, page 52, 94)

[63] Fiber-to-the-Node (FTTN) is not identified as a separate technology of transmission in the Form 477 data. Instead, I define Fiber-to-the-Node (FTTN) as any Asymmetric DSL technology of transmission capable of at least 10 Mbps download and 0.768 kbps upload speeds. Therefore, Asymmetric DSL connections are all those connections that do not reach the speed threshold of 10+/0.768+.

penetrations measured either as a function of the number of households, housing units or population. These findings are consistent with the results from individual crop regions. The data in Table 8 also show improvements in speed thresholds over time from 2008 to 2017.

4. Empirical Strategy

Having presented the data, I turn next to a summary of the estimation strategy. This paper seeks to determine whether broadband penetration at a given speed threshold is associated with improved crop yields and/or lower farm expenses. I use a panel dataset comprised of county-level U.S. farming outcomes and Internet connection counts in 2007/2008, 2012, and 2017, for a total of 9,210 county-year observations in the full sample.

Dependent variables are classified as either an expense (e.g. operating or chemical expenses per operation) or a productivity measure (e.g. corn yields measured in bushels per harvested acre). For crop productivity measures, I estimate the model for the set of counties specializing in the production of each of the selected crops in the sample. For instance, in Column 1 of Table 9, I estimate the regression model for corn yields in all counties with harvested acres of corn. For expense measures, the approach is similar. I estimate the model for the set of counties with any harvested acres of cropland.

The primary independent variable of interest is the broadband penetration rate, or the number of Internet connections with at least 25 Mbps download and 3 Mbps upload speeds per 1,000 households in a county. Additional analysis uses the number of Internet connections with at least 10 Mbps download and 0.768 Mbps upload speeds per 1,000 households in a county. I discuss each component of the empirical strategy in more detail below.

4.1 Fixed Effects Model

The primary relationship of interest is between the change in broadband penetration and farming outcomes over time. I estimate the effect of broadband on farming outcomes using a fixed effects technique, which models the change in farming outcomes as dependent variables and uses varying levels of socioeconomic and other demographic characteristics as explanatory variables. A pooled estimator, which utilizes repeated cross-section data, does not control for either time or county fixed effects, although each observation in the model is assumed to be taken from the same distribution. Coefficients in the fixed effects model represent average changes within counties, only for counties that experienced changes in broadband penetration. This approach approximates estimating an average treatment effect among the treated. This approach is preferred if individual county fixed effects are correlated with other exogenous variables. Generally, a fixed effects technique is more appropriate because the data includes all counties in which a commodity is grown and/or sold, not a sampling of counties across the U.S.[64]

[64] Fixed effects analysis supports inference when a sample exhausts the population (Green and Tukey, 1960).

The fixed effects estimator is based solely on variation within units, and automatically controls for all observable and unobservable unit-specific characteristics:

$$AG_{it} = \beta_0 + \gamma_i + \beta_1 \boldsymbol{X}_{it} + \beta_2 PEN_{it} + \beta_3 T_t + \varepsilon_{it},$$

where AG_{it} is the outcome of interest, farming outcome measures in county *i* at time *t*; γ_i is the unit-specific intercept, the county fixed effect; X_{it} are observed county-level socioeconomic control variables such as income, unemployment rates, education and other demographic characteristics enumerated in Table 7; PEN_{it}, is the variable of interest that measures the broadband penetration rate in county *i* at time *t*; T_t denotes the county-invariant time fixed effects, the coefficients β_1, β_2, and β_3 are associated parameter vectors, and help evaluate the effects of improvements in broadband penetration for farming counties over time, and; ε_{it} is the error term. The data indicate that some estimates of broadband penetration, specifically the number of connections with at least 25 Mbps download and 3 Mbps upload speeds per 1,000 households, are zero for some counties in some time periods. These observations are meaningful zeros instead of missing observations, in the sense that zero connections indicate that no broadband connections exist, and therefore should not be dropped from the analysis. All dependent variables and the primary independent variables of interest are transformed using the inverse hyperbolic sine (Burbidge, Magee and Robb, 1988; MacKinnon and Magee, 1990).[65] The transformation is defined at zero but can be interpreted similarly to a standard logarithmic transformation.

The model controls for several other characteristics that could affect either farm productivity or expense measures.[66] Related literature finds that large corn farms are more profitable and adopt technology earlier than smaller corn farms.[67] Additionally, the size of counties are fixed, but larger operations may exploit economies of scale in crop production that should be controlled for in the analysis. Therefore, the yield regressions include crop-specific average farm size (e.g., for corn yields, I include a variable for harvested acres of corn per corn operation) and workers per operation to capture scale economies at the county level. The expense regressions include a variable for the average number of harvested acres of cropland per cropland farm operation as a scale measure. Other explanatory variables include median household

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[65] From Bellemare and Wichman (2019), applying the inverse hyperbolic sine transformation to a variable x yields a new variable:

$$\tilde{x} = \text{arcsinh}(x) = \ln\left(x + \sqrt{x^2 + 1}\right)$$

The inverse hyperbolic sine transformation is defined for both zeros and negative values, although it is noted that the transformation is not concave for negative values (Ravallion, 2017). However, Bellemare and Wichman (2019) show that the derived elasticities from an arcsinh-arcsinh specification are equivalent to logarithmic transformations (Burbidge et. al., 1988; MacKinnon and Magee, 1990; Pence, 2006). An alternative, but somewhat more complicated, approach would be to represent the broadband penetration rate as two variables, one of which is the log of the independent variable of interest when that variable is non-zero and is set to zero otherwise, and a second variable which is a dummy variable for non-zero Internet penetration (Hosmer and Lemeshow, 2000; Robertson et al., 1994). I rely on the former transformation due to the ease of interpretation.

[66] Some variables, such as share of the county population that is male, does not vary much over each 5-year period and may be subsumed by the fixed effects.

[67] Schimmelpfenning, 2016.

income, unemployment rate, population density, share of male population, share of population 25 and older with high school only education, share of population age 25 and older with some college education only, share of population age 25 and older with bachelor's degree and above, share of the population ages 15-24, ages 25-44, ages 45-64, ages 65-plus and the share of population white, black, or Asian, and the share of population of Hispanic origin.[68]

4.2 Instrumental Variables Model

The primary specification leverages changes in broadband penetration over time and across counties to estimate the effect on farming outcomes, but endogeneity concerns might remain. Standard OLS methods would result in biased estimators and invalid inferences if there exists two-way causality between farm productivity and improved broadband penetration. Demand for broadband may rise with economic growth and farm profitability at the county level. Additionally, there exists the possibility that improvements in farming outcomes are instead driven by omitted factors that are unrelated to increased broadband penetration as specific speed thresholds.

To address this and other concerns, I implement an instrumental variables (IV) approach using two-stage least squares (2SLS) to account for the possibility that broadband penetration is endogenous. The fixed effects modeling relies on the natural variation in broadband penetration rates across counties and time periods in the sample. The IV model relies on variation from the instrument. I construct a version of a Hausman-type instrument for the broadband penetration variable (Hausman, 1997). The assumption is that the instruments are correlated with broadband penetration in a target county but remain uncorrelated with farming outcomes such as crop yields or expenses. For each county i, I instrument for broadband penetration at each threshold in year t using the average broadband penetration rates for the same speed threshold in all adjacent counties.[69] Broadband penetration rates are likely correlated across neighboring counties through network buildouts or through similar topography. However, instrument exogeneity might be violated if spatial correlation of broadband penetration in neighboring counties determines crop production or expenses in county i. The IV models are just identified, and I cannot directly test exogeneity. If the instruments are not exogenous, then the estimates would be biased.

Early research on Internet use indicates that education levels, age, income, and the number of children in the household are demographic determinants for whether households adopt the Internet (Stenberg et al., 2009). Therefore, I also conducted the analysis using a measure of

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[68] Hispanic origin is considered an ethnicity, not a race (https://www.census.gov/topics/population/hispanic-origin/about.html, last accessed Dec. 8, 2020). All explanatory variables are transformed using the inverse hyperbolic sine (variables given as a proportion are also transformed for consistency in the event of zero values; although interpretation may be more difficult in these instances).

[69] An additional Hausman instrument was considered using the average broadband penetration in all counties in the same state as the target county, minus the target county's penetration rate. While the results using the state average broadband penetration rate were generally similar to those using adjacent counties, diagnostics following estimation of the IV model of the former instrument indicate a potential weak instrument problem (the Kleibergen-Paap Wald F statistics were much smaller). Therefore, this paper relies on adjacent county averages as the more appropriate instrument. States are quite large, and there may be less correlation in same-state counties than in adjacent counties that are contiguous. This is even more true if target counties are located near state borders (in which adjacent counties would be removed from the calculation if located in another state).

educational attainment and median household income. Unfortunately, the Ag. Census does not include much demographic information on farm operators, so the instruments were constructed using Census data at the county level. Diagnostics indicated that the education instruments were relatively weak and explained little of the variation in Internet penetrations rates, therefore these results are not included in this study. Median household income performed significantly better as an instrument than education, especially at the 25+/3+ threshold, but diagnostics indicated income was a weak instrument at the 10+/0.768+ threshold. These results are not included in this study.

5. Results

Having presented the empirical methodology, I turn now to the study's main findings. Results for crop yields using the fixed effects (FE) and 2SLS models for the 25+/3+ threshold can be viewed in Table 9; Table 10 displays the crop yield results using the FE and 2SLS models at the 10+/0.768+ threshold. Results for expenses per operation using the FE and 2SLS models for the 25+/3+ threshold can be viewed in Table 11; Table 12 displays the results of the FE and 2SLS specifications for expenses per operation at the 10+/0.768 thresholds. Each column in Tables 9 through 12 corresponds to either a different crop yield or expense measure. The full set of control variables are listed in the footnote of each table.[70] The coefficients of the control variables are not included due to brevity.[71] All models include time and county fixed effects and robust standard errors clustered at the county level.

Coefficient and standard error estimates are displayed for the key variables of interest, which are the Internet penetration rates at either the 25+/3+ or 10+/0.768 speed threshold. As both the dependent variables are transformed using the inverse hyperbolic sine, the coefficients in both specifications can be interpreted as an elasticity. The number of observations and a measure of the goodness of fit are shown for each FE specification. The number of observations, a test for weak instruments (the Kleibergen-Paap (KP) Wald F statistic) and a test for underidentification (the KP rk LM statistic) are shown for the 2SLS regressions.[72] While coefficients under FE and 2SLS are not directly comparable, it may be useful to contrast the results. Generally, the IV standard errors are larger than the FE standard errors. Larger standard errors may indicate weak instruments, however the KP Wald F statistics indicate this is not the case. Instead, the result may confirm the trade-off between bias and efficiency, and the 2SLS

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[70] Additional explanatory variables include county average median household income, unemployment rate, population density, share of population male, share of population with high school only education, share of population with some college education only, share of population with bachelor's degree and above, share of the population ages 15-24, ages 25-44, ages 45-64, ages 25-44, ages 65 plus, share of population white, black and Asian, and population share of Hispanic origin. All control variables are transformed using the inverse hyperbolic sine for consistency, although I note this makes interpretation of some control variables potentially more difficult.

[71] Additionally, coefficients of control variables do not necessarily have a structural interpretation (Cinelli and Hazlett, 2020)

[72] The KP Wald statistic is based on the Stock and Yogo (2005) test of weak instruments using the first-stage F statistic, where the null hypothesis is that the instruments are weak using the Stock-Yogo critical values. The KP Wald statistic is valid when errors are not independent and identically distributed. The KP rk LM statistic tests whether the excluded instruments are correlated with the endogenous regressors, where the null hypothesis is no correlation.

coefficients are in most instances larger than the FE estimates. One possible explanation for larger coefficients under 2SLS is that the FE and 2SLS estimates apply to different populations — the average treatment effect among the treated vs. the local average treatment effect. Other potential reasons are omitted variables which may be biasing the FE estimates downward, or measurement imprecision in the broadband variable of interest.

Several findings are immediately noticeable in the yield regressions in Tables 9 and 10. In the IV regression, the instrument is the average number of 25+/3+ connections per 1,000 households of a target county's contiguous neighboring counties. Diagnostic tests suggest the instrument is strong. Evaluating the effect of changes in 25+/3+ connections on crop yields, I find positive and significant coefficients for most field crop types. Corn, cotton, hay, and soybean yields display positive and significant coefficients for the Internet penetration rate of interest in both the FE and 2SLS regressions in Table 9. Using a 2SLS estimation, I find that a 1% increase in the number 25+/3+ connections per 1,000 households is associated with a 3.63% increase in corn yields (measured in bushels per harvested acre). The coefficient is over two times the magnitude of coefficient in the FE regression, suggesting potential downward bias in the FE estimates. For soybeans, a 1% increase in the number of 25+/3+ connections per 1,000 households is associated with a 3.76% increase in yields (measured in bushels per harvested acres). The coefficient is also over twice as large as the coefficient in the FE regression. For cotton and hay yields, the 2SLS regression indicates that a 1% increase in broadband penetration at 25+/3+ speeds is associated with a 10.1% and 2.15% increase in yields, respectively. The coefficient for cotton yields is four to five times larger than the coefficient in the FE regression, indicating significant downward bias. The diagnostics on the 2SLS regression for cotton yields indicate a strong instrument, but the magnitude of the KP Wald F statistic is much lower than those in other 2SLS regressions illustrated in Table 9. I note that the coefficient on wheat yields is negative under FE and positive under 2SLS, although both are insignificant. Descriptive statistics for wheat regions in Table 6 indicate that the number of counties in which wheat was harvested declined from 2007 through 2017. Therefore, the effect on wheat yields may be due to lack of power, or from counties exiting the sample.

Table 10 replicates the analysis for crop yields using the number of 10+/0.768+ connections per 1,000 households as the key independent variable of interest. Using the 2SLS estimation, I find that a 1% increase in the number 10+/0.768+ connections per 1,000 households is associated with a 5.5% increase in corn yields. For soybeans, a 1% increase in the number of 10+/0.768+ connections per 1,000 households is associated with a 3.55% increase in yields. The coefficient is also over twice as large as the coefficient in the FE regression. In the FE estimation, the coefficient on wheat yields is positive and significant at conventional levels. This suggests that a 1% increase in broadband penetration at 10+/0.768+ speeds is associated with a 0.7% increase in wheat yields (bushels per harvested acre).

The results for the lower speed threshold in Table 10 are not as robust as those for the 25+/3+ threshold in Table 9. The coefficients on cotton and hay yields are negative and economically significant in the 2SLS estimation. It's possible that beneficial yield outcomes in crop-producing counties require a higher speed threshold than 10+/0.768+. Some evidence suggests that some precision agriculture technologies require 25+/3+ connections while others do not.[73] The negative and significant coefficients on cotton and hay crop yields may indicate the imprecision inherent in measuring the types of technological applications that may be used by farm operations at lower thresholds. This connects generally to the study's limitation in being unable to directly tie broadband penetration rates in a county to the use of that connectivity on a farming operation. Last, I cannot rule out that some technologies supported by Internet architecture may be implemented post-harvest. The case study presented in Section 2 on the integration of connected technologies into cotton harvesting indicated that much of the potential gains materialized post-harvest through quality classifications and/or through technologies that may require higher speeds.[74] Therefore, the impact of improved connectivity would show up in expenses for cotton farms rather than in yields, and the data does not allow me to identify expenses for cotton farming alone.

The expense regressions in Tables 11 and 12 illustrate a more mixed result than the yield regressions. In contrast to the results for crop yields, the findings in Tables 11 and 12 indicate a clear benefit in the form of reduced expenses per operation at 10+/0.768+ speeds which appears to dissipate at 25+/3+ speeds. Using the 2SLS estimation, Table 12 indicates that a 1% increase in 10+/0.768+ speeds is associated with a 2.37% decrease in total operating expenses per operation. In Column 2, a 1% increase in 10+/0.768+ speeds is associated with a 2.63% decrease in chemical expenses per operation under the 2SLS estimation. Using the 2SLS estimation, Columns 3 through 5 indicate a 1% increase in the Internet penetration rate at 10+/0.768 speeds is associated with a 6.47%, and 3.43% decline in fertilizer and seed and plants expenses per operation, respectively. I note that while fuel expenses per operation are negative but insignificant in the 2SLS estimation, the coefficient is positive and insignificant in the FE estimation in Table 12. The 2SLS estimations in Table 11 using the broadband penetration rate at 25+/3 speeds show mostly positive but insignificant coefficients for each cost type. Although the coefficient on seed and plants expenses per operation is negative and significant at conventional levels in the FE estimation, it is negative and insignificant in the 2SLS estimation. The coefficient on fertilizer expenses per operation is positive and significant in the 2SLS estimation.

There are many possible reasons for the disparate findings in Tables 11 and 12. First, there may be some efficiency gains that are initially achievable for farm operations at lower speed thresholds but that are less salient at higher thresholds. More importantly, there is significant imprecision in how expenses per operation are measured for the purposes of this study. In Section 3 where I describe the data, I noted that the expense measures, unlike the production measures, were aggregate measures across all farming purposes. Expense measures as defined in the Ag. Census are not restricted to corn or cotton operations, for instance, nor can they be restricted to field crops more generally. Expenses per operation as defined in Tables 11 and 12 include expenses for all farm operation types, such as field crops, nurseries and greenhouses, aquaculture and animal farming. While some types of expenses, such as those for seeds, plants or fertilizer, may be the provenance of farm operations that concentrate on cropland, there is no way to strictly isolate those expenses to corn, cotton, hay, soybean or wheat production, let alone to field crops themselves. Cropland can include not only land for field crops and hay, but land used for vegetables, nursery and greenhouses, orchards, vineyards, citrus

[73] "A Case for Rural Broadband", USDA, April 2019, page 3.
[74] Ge. Y, Thomasson, J.A., and Sui, R. (2012).

groves, Christmas trees, fruits, nuts and berries. And seeds and plant expenses can include the cost of all seeds, bulbs, plants, propagation materials, trees, seed treatments, and seed cleaning costs. One possible alternative specification would be to restrict the expense regressions to only those counties in which the predominant share of total crop sales is derived from a single crop, such as corn or soybeans. However, counties are quite large, and there are only a handful of areas in which corn or soybeans sales comprise 90% or more of total crop sales. In fact, the median corn share of all crop sales is approximately 26%.

5.1 Robustness

I next turn to a set of robustness checks to the main empirical specification, focusing on crop outcomes at the 25+/3+ speed threshold.[75] As an alternative specification, Table 13 reports a limited analysis for crop yields using only the 2012 and 2017 paired data sets at the 25+/3+ speed threshold. The findings generally correspond to the results in Table 9, which uses all three matched time periods. In the 2SLS estimation, a 1% increase in Internet penetration at 25+/3+ speeds are associated with a 2.23% increase in corn yields and a 3.04% increase in soybean yields. For hay yields, the impact of improved connectivity at 25+/3+ is associated with a 1.33% increase in production. The coefficients on cotton and wheat yields are negative but insignificant in the FE estimation, and positive and insignificant at conventional levels in the 2SLS estimation. I also note the coefficients on corn, hay and soybean yields in the restricted sample are slightly smaller than those in the full sample displayed in Table 9. This could be a factor of insufficient data in the restricted time period analysis, or from declining treatment effects over time.

To explore this issue of declining treatment effects, Table 14 reports a second limited analysis for crop yields using only the 2007/2008 and 2012 paired data sets at the 25+/3+ threshold. In the 2SLS estimation in Table 14, the coefficients on corn, hay and soybean yields are positive and significant, and larger than the 2SLS coefficients in either Table 9 or Table 13. This would tend to suggest larger treatment effects captured in the earlier time periods and which dissipate over time. For the limited sample using the early time periods, the coefficient on cotton yields in the IV estimation is approximately the same as that in Table 9 with the full sample, an estimated effect of 9.68% vs. 10.1%. This coefficient was positive but insignificant in the late period limited sample shown in Table 13. This result also suggests declining effects over time. However, I note that the coefficient on wheat yields in Table 14 is negative and insignificant under both the FE and the 2SLS estimation. The coefficient for wheat in the 2SLS estimation was positive and insignificant in Table 9 using the full sample, and positive and insignificant in Table 13 using the early period limited sample. This could suggest a delay in the treatment effect for wheat producing regions, or a process particular to wheat farming not well-captured in the model.

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[75] The various robustness checks in this section were also run for the expense measures, and additionally at 10+/0.768+ speeds for both crops and expenses. The findings of these analyses, while not included in this study, are largely similar to the pattern of results displayed in the main empirical strategy and illustrated in Tables 9 through 12. The strongest association between improved broadband penetration rates and increased crop yields are found at 25+/3+ speeds, as opposed to 10+/0.768+ speeds. For the expense regressions, the strongest association between improved broadband penetration rates and lower expenses per operation are found at 10+/0.768+ speeds, as opposed to 25+/3+ speeds.

Last, I present results using only December 2011 and December 2016 vintages of the Form 477 Internet data paired to the 2012 and 2017 Ag. Censuses. There may be a greater lag between broadband take-up rates and the implementation of that connectivity into agricultural or farm management processes. But to avoid further confounding the timing issue, the first paired time period (2007/2008) is omitted from the analysis. Table 15 reports results of this methodology using Internet penetration rates at 25+/3+ speeds. The results correspond generally to those of the main specification in Table 9. I find that the coefficients on corn, cotton, hay, soybean and wheat yields are positive and significant in the 2SLS estimation. In the FE estimation for wheat yields, the coefficient in Table 15 is positive and insignificant. In Table 9, the wheat yield coefficient was negative and insignificant in the FE estimation, but positive and insignificant in the 2SLS estimation. This could indicate an increased lag for farming in wheat regions that was not picked up in the original specification. Or it may suggest that there is some process or pattern to wheat farming that is not being well-captured in the original timing of the model. In the 2SLS estimation, a 1% increase in the number of 25+/3+ connections per 1,000 households is associated with a 2.44%, 2.81%, 1.81%, 6.05%, and 1.28% increase in corn, cotton, hay, soybean and wheat yields, respectively. Unlike the findings in Table 9, the coefficient on broadband penetration in the FE estimation for cotton yields is negative and insignificant; the coefficient on broadband penetration is positive and economically significant in the 2SLS estimation for cotton yields. Overall, however, the findings in Table 15 using only the latter two December vintages show a similar pattern of results as Table 9, although the coefficients in Table 9 are somewhat larger for corn, cotton and hay. This suggests further analysis would be needed to identify if there is a meaningful lag in the implementation of available Internet.

6. Conclusion

Overall, I find robust evidence that an increase in broadband penetration rates at the 25+/3+ speed thresholds is associated with higher crop yields. The results are particularly robust for corn and soybeans, for which the study found a positive and significant correlation across all alternative specifications, even at the lower 10+/0.768+ speed threshold.[76] This study focused on corn, cotton, hay, soybeans and wheat for two primary reasons. First, they are among the top agricultural commodities produced in the U.S. Second, related literature suggests these field crops are the most likely to benefit from, and thus implement, precision agriculture technologies and other Internet-dependent processes into farm management.

For the expense regressions, I find that an increase in broadband penetration rates at the 10+/0.768+ speed threshold is associated with lower expenses per operation. However, this result does not hold for expenses per operation at the higher 25+/3+ speed threshold. Unlike the crop yield data, the expense measures I examined cannot be limited to either field crops generally or to one crop type such as corn. The expense measures are defined for all agricultural processes covered in the Ag. Census, including animal farming, aquaculture and nursery and greenhouses. Therefore, the results indicate imprecision in the aggregate definition of expenses analyzed in the

[76] Robustness checks were run for costs at the 25+/3+ speed threshold and for both crops and costs at the 10+/0.768+ speed threshold but are not included in the paper.

study and could stem from the inability to directly measure expenses for the types of crops that may be more likely to implement Internet technologies into the farm process. The expense regressions results may also derive from the fact that there may be efficiencies that require a lower speed threshold but for which higher speeds are not additively beneficial.

This study also provides some descriptive evidence of the composition and quality of broadband connectivity in the five crop regions and across the U.S. For all five crop regions, I find that the majority of broadband connections transitioned from Asymmetric DSL technologies to cable modem and FTTN technologies from 2007 through 2017. In addition, counties in these regions experienced an increase in speed thresholds over time. This occurs not only for one-way download and upload speed thresholds, but also for matched download and upload speed thresholds. Therefore, it appears that previously unserved and underserved counties are experiencing increased access and adoption of broadband.

I note several other limitations associated with this study. While the analysis implements a panel comprised on three Form 477 broadband vintages and three waves of the Ag. Census, data limitations preclude a precise match for the earliest time period. Form 477 broadband data was collected at the census tract level beginning only in December 2008, which I match to the December 2007 wave of the Ag. Census. However, robustness checks using only 2012 and 2017 paired data support claims that improved 25+/3+ penetration rates are associated with higher crop yields. In fact, a separate robustness check using only the earlier time periods (2007/2008 and 2012) indicates that a significant portion of the benefits to improved 25+/3+ penetration rates in terms of higher crop yields were captured early, and then displayed declining treatment effects over time.

The study presents a rigorous, quantitative evaluation of the impact of improved Internet connectivity on a variety of farming outcomes. It leveraged in its approach the highly disaggregated data on broadband connections that has been collected by the Commission since 2008. In addition to providing an introductory look at changes over time in the composition of connectivity in regions where a selected set of field crops are produced, the study is a useful addition to the body of research supporting policy recommendations focused on promoting the rapid, expanded diffusion of broadband to unserved and underserved agricultural areas. The Commission and other federal agencies have long expressed commitment to closing the digital divide in rural areas. This paper provides evidence that improved connectivity at higher speed thresholds is an important factor in improving outcomes for U.S. farmers. Limited evidence also suggests that lower speed thresholds may be sufficient to support the realization of some expense savings for U.S. farmers. For those farming activities such as precision agriculture that may indicate a higher speed threshold, further analysis would be necessary. While this study makes no effort to evaluate the cost-benefit analysis of continued institutional support for network buildout in unserved and underserved areas, the results clearly indicate that Internet access meaningfully contributes to rural infrastructure development.

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Appendices

Table 1: County-level Means from Agricultural Census

	2007	2012	2017
General characteristics			
Operated acres (000s)	298.0	297.6	293.3
Harvested acres of cropland (000s)	100.2	102.0	103.6
Total farm operations	716.4	685.2	663.1
Farm operations with harvested cropland acres	430.4	417.9	403.7
Farm operations with acres operated	715.4	684.5	662.4
Crop sales per operation with sales ($000s)	130.9	190.5	174.5
Farm-related income per operation ($000s)	16.2	21.2	21.9
Other farm-related income per operation ($000s)	15.5	16.6	23.4
Selected expense characteristics			
Chemical expenses per operation ($000s)	10.6	15.9	18.8
Operating expenses per operation ($000s)	116.6	166.0	172.8
Feed costs per operation ($000s)	51.3	77.9	64.2
Fertilizer expenses per operation ($000s)	16.4	28.1	23.1
Fuel expenses per operation ($000s) including lubricants	6.7	9.4	8.0
Seeds and plants costs per operation ($000s)	13.3	20.3	25.7
Selected land-use characteristics			
Acres per farm operation treated with fungicide	218.0	258.9	346.2
Acres per farm operation treated with herbicide	308.2	339.7	404.0
Acres per farm operation treated with insecticide (nematicides)	205.7	222.6	316.8
Acres per farm operation treated with fertilizer	284.5	293.9	305.4
Operations with self-propelled (SP) combines	105.0	104.3	98.0
Operations with SP combines (< 5-years-old)	18.9	25.7	20.2
Operations with SP cotton pickers/strippers	20.1	23.7	21.5
Operations with SP cotton pickers/strippers (< 5-years-old)	8.4	7.6	6.7
Operations with SP forage harvesters	21.6	23.0	21.1
Operations with SP forage harvesters (< 5-years-old)	4.2	4.3	4.5
Selected Internet characteristics from Census of Agriculture			
Farm operations with Internet access	405.1	476.9	500.0
Farm operations with high-speed Internet access	236.2	.	.
Farm operations with Internet access over power lines	.	13.6	.
Farm operations with Internet access over cable	.	73.3	97.1
Farm operations with Internet access via dialup	.	46.3	17.0
Farm operations with Internet access via DSL	.	190.7	126.8
Farm operations with Internet access via fiber optics	.	26.6	51.9
Farm operations with Internet access via mobile	.	88.0	193.7
Farm operations with Internet access via other method	.	14.7	18.6
Farm operations with Internet access via satellite	.	93.1	98.7
Farm operations with Internet access via unknown method	.	.	38.0

Note: County-level averages from the 2007, 2012, and 2017 Agricultural Census.

Table 2: Production and Internet Characteristics for Corn Regions

	2007	2012	2017
General Characteristics			
Counties with harvested corn	2319	2352	2332
Farm operations with harvested acres	149.7	147.9	130.4
Harvested acres (000s)	37.2	37.1	36.3
Harvested acres of corn per operation	208.2	210.9	245.7
Yield (bushels / harvested acre)	118.9	106.7	149.1
Overall Internet Penetration Rates			
Number of connections per 1000 housing units	423.4	531.6	615.0
Number of connections per 1000 people	190.2	245.1	289.7
Number of connections per 1000 households	498.5	624.8	721.8
By Technology Type (% of all connections)			
Cable	33.8	35.6	38.5
FTTP	1.9	5.0	11.7
FTTN	0.3	3.0	14.7
Asymmetric DSL	54.8	46.8	23.3
Satellite	5.1	5.6	6.8
Terrestrial Fixed Wireless	3.1	3.2	4.7
Symmetric DSL	0.5	0.3	0.1
Other Copper	0.5	0.5	0.3
Two-way Speed Thresholds (% of all connections)			
3+/0.768+	19.79	46.32	87.38
10+/0.768+	5.94	25.28	66.74
10+/3+	0.25	9.92	44.43
25+/3+	0.04	4.20	38.43
25+/10+	0.04	0.47	14.46
100+/25+	0.01	0.05	2.01
100+/100+	0.01	0.05	1.37
Downspeed Tiers (% of all connections)			
(0.200 to 0.768) Mbps max down	15.61	5.74	0.70
[0.768 to 1.5) Mbps max down	17.74	12.49	2.00
[1.5 to 3) Mbps max down	21.17	16.54	4.49
[3 to 6) Mbps max down	22.84	25.07	13.15
[6 to 10) Mbps max down	15.52	12.38	12.78
[10 to 25) Mbps max down	7.03	23.10	27.08
[25 to 100) Mbps max down	0.03	4.56	28.28
100+ Mbps max down	0.06	0.12	11.51
Upspeed Tiers (% of all connections)			
[0, 200] Mbps max up	13.74	6.68	NA
(0.200 to 0.768) Mbps max up	60.01	41.71	10.22
[0.768 to 1.5) Mbps max up	23.03	30.86	34.16
[1.5 to 3) Mbps max up	2.58	10.21	9.54
[3 to 6) Mbps max up	0.49	9.39	26.75
[6 to 10) Mbps max up	0.08	0.16	2.40
[10 to 25) Mbps max up	0.04	0.69	12.22
[25 to 100) Mbps max up	0.02	0.25	2.61
100+ Mbps max up	0.01	0.05	1.37

Source: County-level averages, Ag. Census and Form 477 data.

Table 3: Production and Internet Characteristics for Cotton Regions

	2007	2012	2017
General Characteristics			
Counties with harvested cotton	469	501	488
Farm operations with harvested acres	39.1	35.8	32.6
Harvested acres (000s)	22.2	18.6	23.1
Harvested acres of per operation	466.5	473.3	595.8
Yield (bales / harvested acre)	1.6	1.8	1.9
Overall Internet penetration rates			
Number of connections per 1000 housing units	372.0	470.2	538.5
Number of connections per 1000 people	160.8	208.4	243.3
Number of connections per 1000 households	447.6	557.0	633.7
By Technology Type (% of all connections)			
Cable	29.7	31.5	33.2
FTTP	1.1	2.6	8.0
FTTN	0.3	3.0	17.1
Asymmetric DSL	58.8	52.4	26.6
Satellite	5.9	6.9	9.6
Terrestrial Fixed Wireless	3.0	2.6	5.1
Symmetric DSL	0.7	0.3	0.0
Other Copper	0.6	0.7	0.4
Two-way Speed Thresholds (% of all connections)			
3+/0.768+	9.99	34.98	83.20
10+/0.768+	2.54	18.52	61.62
10+/3+	0.12	5.33	36.66
25+/3+	0.03	1.70	31.16
25+/10+	0.03	0.15	11.43
100+/25+	0.02	0.03	0.96
100+/100+	0.02	0.03	0.67
Downspeed Tiers (% of all connections)			
(0.200 to 0.768) Mbps max down	16.23	6.68	0.74
[0.768 to 1.5) Mbps max down	19.67	14.01	2.36
[1.5 to 3) Mbps max down	23.46	19.80	5.58
[3 to 6) Mbps max down	22.83	27.84	15.74
[6 to 10) Mbps max down	14.93	10.90	13.75
[10 to 25) Mbps max down	2.86	18.11	29.09
[25 to 100) Mbps max down	0.01	2.59	22.43
100+ Mbps max down	0.02	0.07	10.31
Upspeed Tiers (% of all connections)			
[0, 200] Mbps max up	14.38	8.33	NA
(0.200 to 0.768) Mbps max up	72.67	52.71	14.56
[0.768 to 1.5) Mbps max up	10.84	24.87	35.65
[1.5 to 3) Mbps max up	1.70	8.06	10.76
[3 to 6) Mbps max up	0.29	5.13	24.19
[6 to 10) Mbps max up	0.05	0.26	1.75
[10 to 25) Mbps max up	0.04	0.51	10.10
[25 to 100) Mbps max up	0.01	0.08	1.45
100+ Mbps max up	0.02	0.03	0.67

Source: County-level averages, Ag. Census and Form 477 data.

Table 4: Production and Internet Characteristics for Hay Regions

	2007	2012	2017
General Characteristics			
Counties with harvested hay (total)	3017	3005	3003
Farm operations with harvested acres	288.0	270.5	266.1
Harvested acres (000s)	20.4	18.5	18.9
Harvested acres of hay (total) per operation	81.1	80.2	83.1
Yield (bales / harvested acre)	2.6	2.5	2.9
Overall Internet penetration rates			
Number of connections per 1000 housing units	417.0	526.2	611.1
Number of connections per 1000 people	191.2	247.9	293.8
Number of connections per 1000 households	503.1	630.0	731.4
By Technology Type (% of all connections)			
Cable	32.5	34.5	37.6
FTTP	1.8	4.5	10.7
FTTN	0.3	3.1	15.1
Asymmetric DSL	55.8	47.9	23.9
Satellite	5.5	6.0	7.2
Terrestrial Fixed Wireless	3.0	3.3	5.0
Symmetric DSL	0.7	0.3	0.1
Other Copper	0.5	0.5	0.3
Two-way Speed Thresholds (% of all connections)			
3+/0.768+	19.24	45.70	86.80
10+/0.768+	5.36	25.00	65.65
10+/3+	0.31	9.36	43.32
25+/3+	0.05	3.96	37.39
25+/10+	0.04	0.43	13.57
100+/25+	0.02	0.05	1.83
100+/100+	0.02	0.05	1.26
Downspeed Tiers (% of all connections)			
(0.200 to 0.768) Mbps max down	16.57	6.06	0.70
[0.768 to 1.5) Mbps max down	17.76	12.67	2.09
[1.5 to 3) Mbps max down	21.81	17.58	4.79
[3 to 6) Mbps max down	21.85	24.71	13.75
[6 to 10) Mbps max down	15.68	11.89	12.87
[10 to 25) Mbps max down	6.23	22.60	27.08
[25 to 100) Mbps max down	0.03	4.38	27.22
100+ Mbps max down	0.06	0.11	11.51
Upspeed Tiers (% of all connections)			
[0, 200] Mbps max up	14.22	6.96	NA
(0.200 to 0.768) Mbps max up	59.57	41.60	10.61
[0.768 to 1.5) Mbps max up	22.78	30.77	34.86
[1.5 to 3) Mbps max up	2.75	10.73	9.52
[3 to 6) Mbps max up	0.52	8.88	26.83
[6 to 10) Mbps max up	0.07	0.14	2.32
[10 to 25) Mbps max up	0.05	0.64	11.50
[25 to 100) Mbps max up	0.02	0.23	2.36
100+ Mbps max up	0.02	0.05	1.26

Source: County-level averages, Ag. Census and Form 477 data

Table 5: Production and Internet Characteristics for Soybean Regions

	2007	2012	2017
General Characteristics			
Counties with harvested soybeans	1738	1878	1913
Farm operations with harvested acres	160.3	161.0	158.2
Harvested acres (000s)	36.7	40.5	47.1
Harvested acres of soybeans per operation	220.2	243.7	290.3
Yield (bales / harvested acre)	34.5	37.2	44.8
Overall Internet penetration rates			
Number of connections per 1000 housing units	428.0	532.3	613.0
Number of connections per 1000 people	192.1	245.1	288.5
Number of connections per 1000 households	497.8	621.2	714.4
By Technology Type (% of all connections)			
Cable	35.1	36.5	38.7
FTTP	2.2	5.2	12.0
FTTN	0.3	2.8	14.7
Asymmetric DSL	53.6	46.3	22.9
Satellite	4.9	5.5	6.9
Terrestrial Fixed Wireless	3.1	2.9	4.4
Symmetric DSL	0.4	0.3	0.1
Other Copper	0.5	0.4	0.3
Two-way Speed Thresholds (% of all connections)			
3+/0.768+	19.88	45.16	87.60
10+/0.768+	6.31	25.22	67.38
10+/3+	0.25	10.12	44.71
25+/3+	0.05	4.21	38.36
25+/10+	0.04	0.45	14.49
100+/25+	0.02	0.03	1.94
100+/100+	0.02	0.03	1.33
Downspeed Tiers (% of all connections)			
(0.200 to 0.768) Mbps max down	15.30	5.73	0.70
[0.768 to 1.5) Mbps max down	17.70	12.79	2.01
[1.5 to 3) Mbps max down	20.71	15.94	4.37
[3 to 6) Mbps max down	22.98	25.47	12.90
[6 to 10) Mbps max down	15.76	11.80	12.50
[10 to 25) Mbps max down	7.46	23.59	27.75
[25 to 100) Mbps max down	0.03	4.58	28.70
100+ Mbps max down	0.06	0.09	11.07
Upspeed Tiers (% of all connections)			
[0, 200] Mbps max up	13.91	6.75	NA
(0.200 to 0.768) Mbps max up	60.57	43.38	10.15
[0.768 to 1.5) Mbps max up	22.36	29.34	33.79
[1.5 to 3) Mbps max up	2.48	9.80	9.69
[3 to 6) Mbps max up	0.52	9.57	26.82
[6 to 10) Mbps max up	0.08	0.14	2.38
[10 to 25) Mbps max up	0.04	0.76	12.47
[25 to 100) Mbps max up	0.02	0.25	2.63
100+ Mbps max up	0.02	0.03	1.33

Source: County-level averages, Ag. Census and Form 477 data

Table 6: Production and Internet Characteristics for Wheat Regions

	2007	2012	2017
General Characteristics			
Counties with harvested wheat	2057	2144	1901
Farm operations with harvested acres	77.8	68.5	54.7
Harvested acres (000s)	24.7	22.8	20.3
Harvested acres of wheat per operation	218.6	219.3	241.6
Yield (bales / harvested acre)	44.8	51.5	55.7
Overall Internet penetration rates			
Number of connections per 1000 housing units	423.5	530.3	622.1
Number of connections per 1000 people	190.4	244.0	292.2
Number of connections per 1000 households	499.5	623.5	729.5
By Technology Type (% of all connections)			
Cable	32.9	34.6	38.1
FTTP	2.1	5.1	12.1
FTTN	0.3	3.1	14.9
Asymmetric DSL	54.6	46.9	22.3
Satellite	5.2	5.8	6.3
Terrestrial Fixed Wireless	3.6	3.8	5.9
Symmetric DSL	0.8	0.3	0.1
Other Copper	0.5	0.5	0.3
Two-way Speed Thresholds (% of all connections)			
3+/0.768+	18.77	45.15	87.48
10+/0.768+	5.50	24.67	66.55
10+/3+	0.24	9.88	44.68
25+/3+	0.06	4.20	38.41
25+/10+	0.05	0.45	14.10
100+/25+	0.03	0.06	2.03
100+/100+	0.03	0.05	1.35
Downspeed Tiers (% of all connections)			
(0.200 to 0.768) Mbps max down	16.37	5.93	0.71
[0.768 to 1.5) Mbps max down	17.78	12.97	1.97
[1.5 to 3) Mbps max down	21.77	17.32	4.54
[3 to 6) Mbps max down	21.97	24.79	13.53
[6 to 10) Mbps max down	15.32	12.11	12.49
[10 to 25) Mbps max down	6.67	22.10	27.15
[25 to 100) Mbps max down	0.03	4.65	27.70
100+ Mbps max down	0.08	0.12	11.90
Upspeed Tiers (% of all connections)			
[0, 200] Mbps max up	13.61	6.68	NA
(0.200 to 0.768) Mbps max up	60.66	42.66	10.03
[0.768 to 1.5) Mbps max up	22.58	30.12	34.13
[1.5 to 3) Mbps max up	2.55	10.03	9.37
[3 to 6) Mbps max up	0.44	9.37	27.16
[6 to 10) Mbps max up	0.07	0.16	2.44
[10 to 25) Mbps max up	0.04	0.70	12.28
[25 to 100) Mbps max up	0.02	0.22	2.55
100+ Mbps max up	0.03	0.05	1.35

Source: County-level averages, Ag. Census and Form 477 data

Table 7: County-Level Means

	2007	2012	2017
General Characteristics			
Metropolitan counties (1 = Yes) (USDA-ERS)	0.3	0.4	0.4
% farm proprietors' employment (BEA)	19.2	18.2	17.2
Unemployment rate (BLS)	4.9	7.8	4.6
Census data			
Median age	40.4	40.8	41.5
Median household income ($)	42,555.4	44,690.1	50,925.9
Population	98,861.4	100,494.9	104,130.6
Housing units	41,325.2	42,512.9	43,976.8
Households	36,037.7	37,579.7	39,004.4
% population male	49.97	50.03	50.10
% population age 25+ high school graduate only	36.0	34.9	34.5
% population age 25+ with some college only	20.5	21.9	21.8
% population age 25+ with bachelor's degree or more'	18.6	20.0	21.1
% population between ages 15 and 24	12.9	13.0	12.5
% population between ages 25 and 44	23.7	23.3	23.3
% population between ages 45 and 64	28.2	28.0	26.9
% population between ages 65 and above	16.0	16.8	18.9
% population Hispanic only	7.8	8.7	9.5
% population Black only	8.9	9.0	9.2
% population Asian only	1.0	1.2	1.4
% population Other only	3.3	3.7	4.1
Quarterly Census of Employment and Wages (BLS)			
Total establishments	2,705.9	2,742.8	2,932.8
No. establishments in agricultural sector	31.3	31.7	34.0
No. establishments in crop production	16.5	16.7	17.6
Total employed in all establishments	42,260.8	41,030.5	44,759.7
Average annual pay ($)	31,684.7	35,761.9	39,926.4

Note: An establishment is a single physical location where one predominant activity occurs (BLS). According to the U.S. Census, a household includes people who are living in a housing structure and housing units describe the actual structure in which residents live. For 2007, household counts derived from 2005-2009 ACS 5-Year Estimates, while for 2012 and 2017, household counts derived from FCC Staff Block Estimates.

Table 8: Characteristics of Broadband Subscriptions

	2008	2012	2017
Number of connections per 1000 households	506.2	632.9	735.0
Number of connections per 1000 housing units	419.1	527.5	612.8
Number connections per 1000 people	192.5	249.1	295.1
Number of residential connections per 1000 households	451.2	569.9	664.1
Number of residential connections per 1000 housing units	374.3	475.6	554.3
Number of residential connections per 1000 people	171.4	224.1	266.5
Number of non-residential connections per 1000 households	55.0	63.0	70.9
Number of non-residential connections per 1000 housing units	44.8	51.8	58.5
Number of non-residential connections per 1000 people	21.0	24.9	28.7
Number 100+/100+ connections per 1000 people	0.0	0.1	4.2
Number 100+/25+ connections per 1000 people	0.0	0.1	6.3
Number 25+/3+ connections per 1000 people	0.1	11.4	118.6
Number 10+/1+ connections per 1000 people	12.7	68.2	198.8
Number 3+/1+ connections per 1000 people	43.3	120.2	259.0
Fixed terrestrial Internet connections per 1000 households	485.4	602.1	691.1
Fixed terrestrial Internet connections per 1000 housing units	402.6	502.8	577.4
Fixed terrestrial Internet connections per 1000 people	184.5	236.8	277.3
Fixed terrestrial connections at 100+/100+ per 1000 people	0.0	0.1	4.2
Fixed terrestrial connections at 100+/25+ per 1000 people	0.0	0.1	6.3
Fixed terrestrial connections at 25+/3+ per 1000 people	0.1	11.4	116.1
Fixed terrestrial connections at 10+/1+ per 1000 people	12.7	67.4	185.7
Fixed terrestrial connections at 3+/1+ per 1000 people	43.3	119.2	242.7

Note: County-level averages derived from internal FCC Form 477 data. Fixed terrestrial Internet comprised of connections from Asymmetric and Symmetric DSL, fixed terrestrial wireless, cable modem, other copper wireline, fiber to the home, electric power line and other wired connections. It does not include satellite.

Table 9: Crop Yield Regressions at 25+/3+ Connection Speeds

	(1) Corn yield (FE)	(2) Cotton yield (FE)	(3) Hay yield (FE)	(4) Soybean yield (FE)	(5) Wheat yield (FE)
Log number of 25+/3+ connections per 1,000 households	0.0158*** (4.14)	0.0185** (2.90)	0.0102*** (5.38)	0.0173*** (4.92)	-0.00179 (-0.73)
Observations	6620	1346	8315	5272	5720
F	135.1	12.38	38.71	108.5	48.34
Adj. R-Squared	0.569	0.495	0.714	0.527	0.700
	(1) (2SLS)	(2) (2SLS)	(3) (2SLS)	(4) (2SLS)	(5) (2SLS)
Log number of 25+/3+ connections per 1,000 households	0.0363*** (5.58)	0.101*** (6.26)	0.0215*** (6.14)	0.0376*** (6.04)	0.000946 (0.22)
Observations	6620	1346	8315	5272	5720
KP Wald F Stat	1574.9	158.5	1918.8	1258.8	1306.2
KP rk LM Stat	749.8	89.03	931.7	589.8	641.7

Note: Corn, soybean and wheat yields in bushels per harvested acre; cotton yield in bales per harvested acre, and; hay yield in dry tons per harvested acre. Each regression includes a measure for average crop-specific farm size and average workers per farm operation. Other controls include median household income, unemployment rate, population density, share of population male, share of population with high school only education, share of population with some college education only, share of population with bachelor's degree and above, share of the population ages 15-24, ages 25-44, ages 45-64, age 65 and above, share of population white, black and Asian, and population share of Hispanic origin (Robust *t* statistics in parentheses $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table 10: Crop Yield Regressions at 10+/0.768+ Connection Speeds

	(1) Corn yield (FE)	(2) Cotton yield (FE)	(3) Hay yield (FE)	(4) Soybean yield (FE)	(5) Wheat yield (FE)
Log number of 10+/1+ connections per 1,000 households	0.0142*** (3.32)	0.00259 (0.35)	-0.00218 (-0.90)	0.0198*** (4.24)	0.00738* (2.18)
Observations	6620	1346	8315	5272	5720
F	134.8	11.72	37.51	111.6	48.40
Adj. R-Squared	0.568	0.491	0.712	0.527	0.701
	(1) (2SLS)	(2) (2SLS)	(3) (2SLS)	(4) (2SLS)	(5) (2SLS)
Log number of 10+/1+ connections per 1,000 households	0.0550*** (6.45)	-0.0467** (-2.62)	-0.0199*** (-4.06)	0.0355*** (4.18)	0.00107 (0.15)
Observations	6620	1346	8315	5272	5720
KP Wald F Stat	1120.1	171.6	1193.6	795.9	778.0
KP rk LM Stat	476.3	93.19	541.4	357.9	361.7

Note: Corn, soybean and wheat yields in bushels per harvested acre; cotton yield in bales per harvested acre, and; hay yield in dry tons per harvested acre. Each regression includes a measure for average crop-specific farm size and average workers per farm operation. Other controls include median household income, unemployment rate, population density, share of population male, share of population with high school only education, share of population with some college education only, share of population with bachelor's degree and above, share of the population ages 15-24, ages 25-44, ages 45-64, age 65 and above, share of population white, black and Asian, and population share of Hispanic origin (Robust *t* statistics in parentheses $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table 11: Expense Regressions at 25+/3+ Connection Speeds

	(1) Operating expenses (FE)	(2) Chemical expenses (FE)	(3) Fertilizer expenses (FE)	(4) Fuel expenses (FE)	(5) Seed, plants expenses (FE)
Log number of 25+/3+ connections per 1,000 households	-0.00168	-0.00274	0.00378	0.000342	-0.00621^{+}
	(-0.86)	(-0.97)	(1.48)	(0.18)	(-1.95)
Observations	9171	8945	9059	9146	8908
F	382.8	322.2	334.1	210.8	376.8
Adj. R-Squared	0.965	0.956	0.959	0.949	0.933
	(1) (2SLS)	(2) (2SLS)	(3) (2SLS)	(4) (2SLS)	(5) (2SLS)
Log number of 25+/3+ connections per 1,000 households	0.000644	0.0000671	0.0137**	0.00406	-0.00247
	(0.20)	(0.01)	(3.02)	(1.18)	(-0.46)
Observations	9171	8945	9059	9146	8908
KP Wald F Stat	2189.4	2080.5	2152.7	2174.5	2064.2
KP rk LM Stat	1031.8	994.8	1017.5	1027.9	989.6

Note: Expenses measures are per farm operation. Each regression includes a measure for average farm size. Other controls include median household income, unemployment rate, population density, share of population male, share of population with high school only education, share of population with some college education only, share of population with bachelor's degree and above, share of the population ages 15-24, ages 25-44, ages 45-64, age 65 and above, share of population white, black and Asian, and population share of Hispanic origin (Robust *t* statistics in parentheses $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table 12: Expense Regressions at 10+/0.768+ Connection Speeds

	(1) Operating expenses (FE)	(2) Chemical expenses (FE)	(3) Fertilizer expenses (FE)	(4) Fuel expenses (FE)	(5) Seed, plants expenses (FE)
Log number of 10+/1+ connections per 1,000 households	-0.00420	-0.00421	-0.0139***	0.00425	-0.00950*
	(-1.51)	(-1.16)	(-4.26)	(1.60)	(-2.08)
Observations	9171	8945	9059	9146	8908
F	385.5	321.2	336.7	210.4	377.8
Adj. R-Squared	0.965	0.956	0.960	0.949	0.934
	(1) (2SLS)	(2) (2SLS)	(3) (2SLS)	(4) (2SLS)	(5) (2SLS)
Log number of 10+/1+ connections per 1,000 households	-0.0237***	-0.0263***	-0.0647***	-0.00554	-0.0343***
	(-4.19)	(-3.47)	(-9.94)	(-1.05)	(-3.52)
Observations	9171	8945	9059	9146	8908
KP Wald F Stat	1455.2	1356.4	1414.1	1442.6	1351.0
KP rk LM Stat	660.3	625.6	644.9	656.0	622.2

Note: Expenses measures are per farm operation. Each regression includes a measure for average farm size. Other controls include median household income, unemployment rate, population density, share of population male, share of population with high school only education, share of population with some college education only, share of population with bachelor's degree and above, share of the population ages 15-24, ages 25-44, ages 45-64, age 65 and above, share of population white, black and Asian, and population share of Hispanic origin (Robust *t* statistics in parentheses $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table 13: 2012/2017 Crop Yield Regressions at 25+/3+ Connection Speeds

	(1) Corn yield (FE)	(2) Cotton yield (FE)	(3) Hay yield (FE)	(4) Soybean yield (FE)	(5) Wheat yield (FE)
Log number of 25+/3+ connections per 1,000 households	0.0106^{*} (2.15)	-0.00555 (-0.85)	0.00361 (1.59)	0.0101^{**} (2.58)	-0.00155 (-0.48)
Observations	4292	862	5802	3528	3554
F	108.5	6.609	34.49	55.88	9.355
Adj. R-Squared	0.542	0.674	0.770	0.550	0.766
	(1) (2SLS)	(2) (2SLS)	(3) (2SLS)	(4) (2SLS)	(5) (2SLS)
Log number of 25+/3+ connections per 1,000 households	0.0223^{*} (2.56)	0.0250 (1.52)	0.0133^{**} (3.07)	0.0304^{***} (4.40)	0.00338 (0.53)
Observations	4292	862	5802	3528	3554
KP Wald F Stat	873.0	91.37	1003.4	717.5	587.7
KP rk LM Stat	495.9	65.96	576.7	422.8	349.7

Note: Corn, soybean and wheat yields in bushels per harvested acre; cotton yield in bales per harvested acre, and; hay yield in dry tons per harvested acre. Each regression includes a measure for average crop-specific farm size and average workers per farm operation. Other controls include median household income, unemployment rate, population density, share of population male, share of population with high school only education, share of population with some college education only, share of population with bachelor's degree and above, share of the population ages 15-24, ages 25-44, ages 45-64, age 65 and above, share of population white, black and Asian, and population share of Hispanic origin (Robust *t* statistics in parentheses $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table 14: 2007/2008 and 2012 Crop Yield Regressions at 25+/3+ Connection Speeds

	(1) Corn yield (FE)	(2) Cotton yield (FE)	(3) Hay yield (FE)	(4) Soybean yield (FE)	(5) Wheat yield (FE)
Log number of 25+/3+ connections per 1,000 households	0.0170^{***} (3.68)	0.0183^{*} (2.14)	0.0131^{***} (5.47)	0.0188^{***} (4.08)	-0.00245 (-0.79)
Observations	4288	862	4876	3334	3794
F	22.79	18.05	32.60	29.97	36.28
Adj. R-Squared	0.510	0.541	0.702	0.469	0.689
	(1) (2SLS)	(2) (2SLS)	(3) (2SLS)	(4) (2SLS)	(5) (2SLS)
Log number of 25+/3+ connections per 1,000 households	0.0478^{***} (6.33)	0.0968^{***} (4.80)	0.0247^{***} (5.90)	0.0427^{***} (5.52)	-0.000256 (-0.05)
Observations	4288	862	4876	3334	3794
KP Wald F Stat	1168.2	107.6	1344.3	946.6	1033.0
KP rk LM Stat	597.9	64.53	664.3	479.7	518.7

Note: Corn, soybean and wheat yields in bushels per harvested acre; cotton yield in bales per harvested acre, and; hay yield in dry tons per harvested acre. Each regression includes a measure for average crop-specific farm size and average workers per farm operation. Other controls include median household income, unemployment rate, population density, share of population male, share of population with high school only education, share of population with some college education only, share of population with bachelor's degree and above, share of the population ages 15-24, ages 25-44, ages 45-64, age 65 and above, share of population white, black and Asian, and population share of Hispanic origin (Robust *t* statistics in parentheses $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table 15: Crop Yield Regressions at 25+/3+ Connection Speeds (December Vintages)

	(1) Corn yield (FE)	(2) Cotton yield (FE)	(3) Hay yield (FE)	(4) Soybean yield (FE)	(5) Wheat yield (FE)
Log number of 25+/3+ connections per 1,000 households	0.0149^{**} (2.94)	-0.00766 (-1.10)	0.00271 (1.22)	0.0160^{***} (3.85)	0.00288 (0.88)
Observations	4292	862	5802	3528	3554
F	108.8	6.608	34.18	56.25	9.380
Adj. R-Squared	0.542	0.674	0.770	0.552	0.766
	(1) (2SLS)	(2) (2SLS)	(3) (2SLS)	(4) (2SLS)	(5) (2SLS)
Log number of 25+/3+ connections per 1,000 households	0.0244^{*} (2.52)	0.0281^{+} (1.65)	0.0181^{***} (3.81)	0.0605^{***} (7.20)	0.0128^{+} (1.86)
Observations	4292	862	5802	3528	3554
KP F Stat	718.1	68.69	758.9	570.5	448.3
KP rk LM Stat	467.3	47.29	522.6	382.5	323.4

Note: Corn, soybean and wheat yields in bushels per harvested acre; cotton yield in bales per harvested acre, and; hay yield in dry tons per harvested acre. Each regression includes a measure for average crop-specific farm size and average workers per farm operation. Other controls include median household income, unemployment rate, population density, share of population male, share of population with high school only education, share of population with some college education only, share of population with bachelor's degree and above, share of the population ages 15-24, ages 25-44, ages 45-64, age 65 and above, share of population white, black and Asian, and population share of Hispanic origin (Robust t statistics in parentheses $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).